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Structural Analysis and Three-Dimensional Modelling of the Southwestern Sudbury Basin: Implications and Recommendations for Mineral Exploration

2003

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ONTARIO GEOLOGICAL SURVEY

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Structural Analysis and Three-Dimensional Modelling of the Southwestern Sudbury Basin: Implications and Recommendations for Mineral Exploration

by

A.J. Dubois and K. Benn

2003

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Abstract

The work presented in this report was conducted as part of the Sudbury Targeted Geoscience Initiative (TGI). The present study was designed to gain a better understanding of the tectonic deformation of the Sudbury Structure, one of the world's largest Ni-Cu-PGE mining camps. The term Sudbury Structure refers to the impact crater, the crystallized melt sheet (Sudbury Igneous Complex) that is part of the crater, offset dikes that are linked to the Sudbury Igenous Complex, the fallback breccia generated by the impact and the adjacent footwall rocks that were deformed during the impact event. The work is focussed on one of the most structurally complex parts of the Sudbury Structure, an area of 220 km^2 in Trill, Drury, Denison and Fairbank townships, in the southwestern part of the Sudbury Basin. The study area is strongly deformed, resulting in modification of the pre-existing Sudbury Structure. This is the first detailed structural study in the western Sudbury Basin. The results are expected to contribute to a revised framework for mineral exploration in that region.

During the summers of 2001 and 2002, over 450 outcrops were mapped and oriented hand specimens were collected for petrographic and microstructural analysis. Also, the cores from several diamond-drill holes, provided by industry, were relogged for rock types and structures. The relogging of the diamond-drill cores provided important information on the three-dimensional structural geometry of the study area. In particular, the structural repetition of the Sudbury Igneous Complex and the footwall rocks is documented.

The study area is divided into 3 zones according to the deformational history: 1) the northwest corner, where ductile deformation is weak or absent; 2) a northeast-southwest trending zone of strongly sheared rocks that corresponds to the South Range shear zone; and 3) a southern portion that is interpreted to lie within the hanging-wall block of the South Range shear zone. Structures within the South Range shear zone indicate that the ductile shearing resulted from a south-over-north oblique thrusting, with a minor dextral component, as previously documented to the east of the study area. The South Range shear zone is itself made up of (possibly) anastomosing mylonitic shear zones. The regions between the shear zones are characterized by systems of anastomosing (possibly conjugate) vertical shear zones, wherein lineations suggest a bulk pure shear with a vertical maximum principal elongation. The South Range shear zone is thus characterized by strain partitioning, with thrusting partitioned mainly on dextral oblique shear zones, and a bulk pure shear in the rocks bounded by the shear zones. Shear zones are hydrothermally altered locally, suggesting fluid movement during ductile deformation. Importantly, the study of diamond-drill cores suggests that the early deformation in the South Range shear zone affected the Sudbury Igneous Complex prior to its final solidification.

The results of mapping, petrographic studies and relogging of drill cores are incorporated into three-dimensional structural models of the study area. Several models were used to test hypotheses on the structural evolution of the study area. The results reveal that an early stage of normal faulting is required to explain the map pattern and the structural repetitions documented in the drill cores. The early stage of normal faulting was most likely coincident with the cooling of the Sudbury Igneous Complex and may have been due to collapse of the walls of the crystallizing melt body.

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Introduction

The Sudbury Targeted Geoscience Initiative (TGI) was a 3-year program (2000–2003) (Ames et al. 2001; Ames 2002) designed to gain a better understanding of 1) the geological setting of one of the world's largest nickel-copper-platinum group element (PGE) deposits, associated with the Sudbury Igneous Complex (SIC); and 2) the processes involved in ore deposit genesis and subsequent deformation. The Sudbury TGI is a collaborative project that involves the Geological Survey of Canada, the Ontario Geological Survey, mining industry partners and several universities, including the University of Ottawa.

This study was initiated in 2001 as part of the Sudbury TGI. It is an investigation of the lithologic and, especially, structural controls on nickel-copper-platinum group element (PGE) mineral deposits in the SIC and its immediate footwall (Dubois and Benn 2001, 2002, 2003). This two-year project, supported by the Ontario Geological Survey and the University of Ottawa, involved extensive mapping in the southwest part of the SIC and its footwall, as well as petrographic studies, relogging of selected diamond-drill cores and three-dimensional modelling of the study area. It emphasized the identification, description and classification of structures related to pre-, syn- and post-SIC deformation events. The project also aimed to propose possible models for the post-Sudbury event deformational history of the southwestern part of the Sudbury Basin.

The area was selected for mapping and structural analysis because it has undergone a large degree of deformation that has strongly modified the Sudbury Structure (Shanks and Schwerdtner 1991a). This makes the study area particularly interesting for an analysis of the deformational history. Unravelling the complex geological structure may lead to revisions of mineral exploration strategies and to the identification of new mineral exploration targets.

LOCATION, ACCESS AND MINING ACTIVITIES

The study area is located approximately 20 km west of Sudbury. It encompasses roughly 220 km^2 and includes parts of Trill, Drury, Fairbank and Denison townships (Figure 1). The southern part of the studied area is accessible by two west to east trending main roads: the Trans-Canada Highway (Highway 17) and Highway 658. Three roads enter the northern part of the study area and they can be accessed from Highway 658. The westernmost road is the regular access to Fairbank Provincial Park, west of Fairbank Lake, and it is linked to Highway 144. The middle road allows access to the Crean Hill and Lockerby mines, and to the eastern part of Fairbank Lake. The eastern, north-trending road is closed to the public in its southern part, but it is open past the Lockerby Mine and connects with Highway 144 further north. Many snowmobile trails and logging roads extend from those roads.

Several rivers link lakes and swamps; they are quite narrow and are not normally navigable by canoe. Major east-trending power lines traverse the area between Fairbank Lake and the village of Worthington. Survey trails below power lines are accessible by foot or with all-terrain vehicles.

The study area includes active and past-producing mines (*see* Figure 1) that are located on the Worthington Offset dike (Victoria Mine, Kidd Copper Mine, Totten Mine and Worthington Mine); and at the contact between the Sudbury Igneous Complex and the footwall (Chicago Mine, Sultana Mine, Crean Hill Mine (INCO) and the Lockerby Mine (Falconbridge Limited)). Thousands of tons of ore were extracted from the Victoria Mine, and 3500 tons of nickel and copper were extracted between 1891 and 1897, from the Chicago Mine (Card 1965). At present, only the Crean Hill Mine and the Lockerby Mine are active.

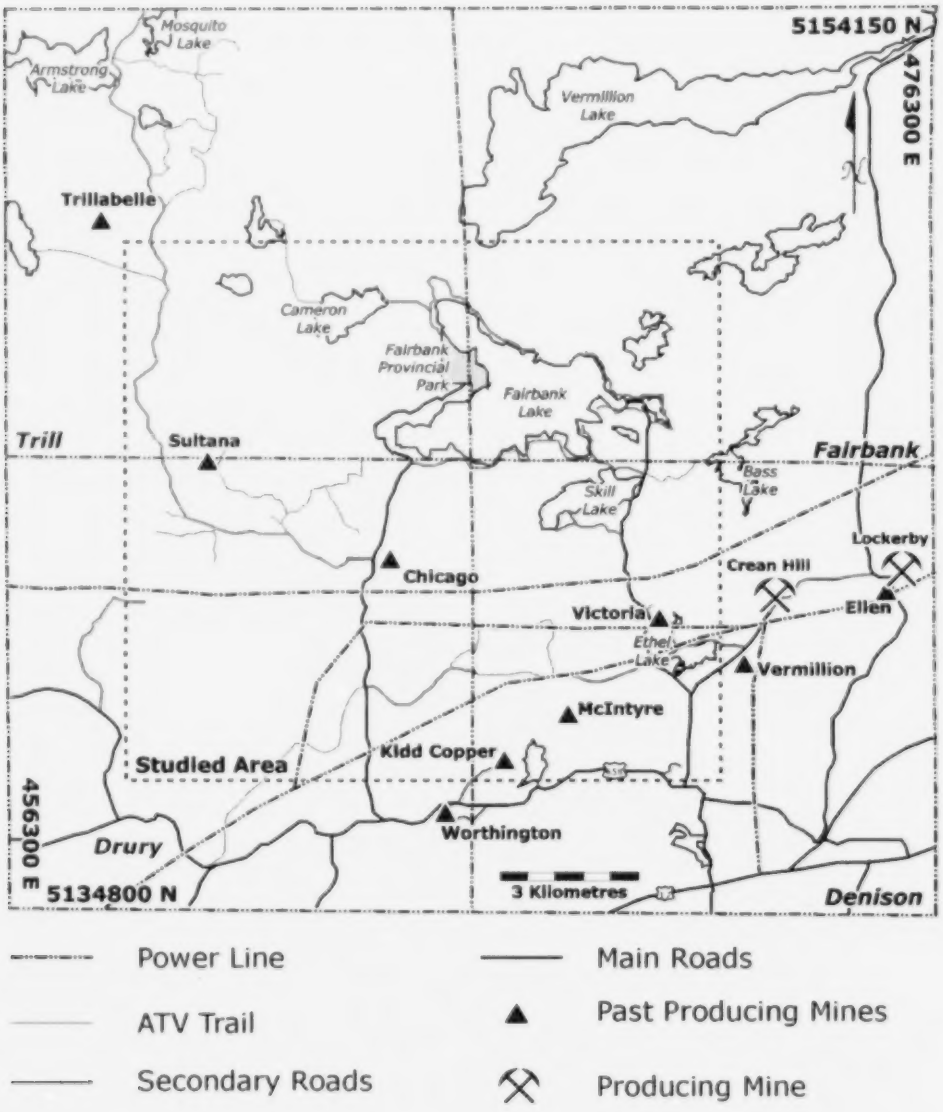

Figure 1. Locations of mines and access roads in Trill, Drury, Denison and Fairbank townships.

Several companies and prospectors have active mining claims in the study area, including INCO, Falconbridge Limited and FNX Mining Company. Mining companies have carried out diamond drilling in the area for at least 60 years; in particular, Falconbridge Limited has diamond-drill logs for approximately 60 km of core. Diamond-drilling programs were not reported in the study area during the summer of 2001. FNX Mining Company started an exploration campaign in 2002, including diamond-drilling near the Victoria Mine. Ground and airborne geophysical surveys have been carried out by private companies and also by government agencies over a long period of time.

DATA SOURCES

The geology of the Sudbury basin has been studied for more than 100 years, during which time a huge database was accumulated. Much of the data are owned by mining companies and are not readily available to the public. Different data sets in the public domain are not necessarily compatible with each other; for instance, not all workers use the same petrologic classifications for rocks of the Sudbury Igneous Complex. Data gathering and synthesis in the study area was performed during the first year of this project and provides the basis of a new, more comprehensive and homogeneous database.

FIELD WORK

Field data were collected during two field seasons, of three months each in 2001 (Dubois and Benn 2001) and 2002 (Dubois and Benn 2002, 2003). In total, 457 outcrops were studied. Approximately one outcrop per 1 km^2 was mapped at 1:50 000, with more detailed mapping concentrated in specific regions.

Topographic elevation in the study area varies between 250 and 400 m above sea level. The vegetation is no longer as sparse as reported by Card (1965), but numerous areas are not fully covered by vegetation. Outcrops situated on topographic highs (hills, ridges) are composed mainly of granite, gabbro and quartz-rich metasedimentary rocks. Outcrops along the sides of the two main north-south roads, which transect the study area, provide observation points into pelitic metasedimentary rocks that are generally found at lower topographic elevations. Topographic highs and roadside outcrops allow for a regular geographical distribution of observations. All outcrop locations were determined using a hand-held global positioning system unit and digital geological maps were prepared using the ArcView3.2® software.

Structural measurements of foliations and lineations, shear zones, faults and folds were compiled. Sampling of oriented hand specimens was performed at regularly spaced intervals to identify rock types and microstructures. The various styles of sulphide mineralization in the study area were documented and studied.

Falconbridge Limited, INCO and FNX Mining Company Inc. allowed the authors to access a selection of diamond-drill cores from Trill, Denison, Drury and Fairbank townships. The cores were relogged with particular attention to structural elements like foliation, lineation, slickensides, etc. Rock types were also noted and verified in thin section. In some cases, petrographic observations showed that rock types had previously been misidentified. Such errors are perfectly understandable because the rock is locally affected by a rather strong greenschist facies overprint due to a static metamorphic event, which resulted in several rock types exhibiting a similar dark green colour in hand specimen. The detailed studies of diamond-drill core have provided important information on the rock units and structures that are present in the subsurface, to about 1500 m depth below the map area.

ACKNOWLEDGEMENTS

We would like to thank the Ontario Geological Survey (OGS) for providing most of the funding for this work under an Ontario Geological Survey–University of Ottawa Collaborative Project Agreement and for providing extensive field logistical support. We are also grateful to INCO, Falconbridge Limited and FNX Mining Company who generously allowed us to access their diamond-drill cores and also their properties, and who provided valuable discussions on Sudbury geology. Wallbridge Mining Company Limited provided field accommodation during the first year of the study.

Geological History of the Study Area

The general geology of the study area is shown in Figure 2. The western part of the study area consists of Neoarchean (>2600 Ma) granitic plutons, gneisses, metavolcanic and metasedimentary units of the Superior Province. In the southern part of the study area, the Neoarchean rocks are unconformably overlain by metasedimentary rocks of the Paleoproterozoic Huronian Supergroup (2500 to 2219 Ma; Card, Innes and Debicki 1977; Corfu and Andrews 1986), which belongs to the Southern Province.

The Murray fault zone, which is a major structural feature in the southern part of the Sudbury Structure, is thought to have originated as an extensional fault during Huronian sedimentation (Card and Hutchinson 1972). Metasedimentary rocks of the lower Huronian Supergroup are intruded by granite plutons ($2388^{+20}/_{-13}$ Ma and 2477±9 Ma; Krogh, Davis and Corfu 1984; Krogh, Kamo and Bohor 1996). The metasedimentary and metavolcanic rocks of the Huronian Supergroup were folded prior to the intrusion of gabbro sills of the Nipissing intrusive suite at approximately 2219 Ma (Card 1978; Bennett, Dressler and Robertson 1991).

The Penokean Orogeny, between 1890 and 1830 Ma (e.g., Van Schmus 1980; Hoffman 1989), deformed the Sudbury Structure. It caused a regional shortening event that resulted in large-scale folding and displacement along south-dipping thrust faults (Zolnai, Price and Helmstaedt 1984). The Penokean Orogeny deformed the Huronian Supergroup and is thought to have reactivated the Murray fault zone as a south-dipping thrust fault (Cooke 1946).

The Sudbury event, widely believed to have been a meteorite impact (Dietz 1964) that created the Sudbury Igneous Complex, the quartz-dioritic offset dikes (e.g., Worthington, *see* Figure 2) and the Sudbury breccias, occurred at 1850 Ma (Krogh, Davis and Corfu 1984). The Sudbury Igneous Complex is interpreted to represent the solidified products of melts generated during the hypervelocity impact event (e.g., Therriault, Fowler and Greive 2002). It is a tripartite magmatic assemblage consisting of norite, which overlies the footwall breccia that forms the base of the igneous complex, gabbro and granophyre. The initial shape of the Sudbury Igneous Complex may have been that of a flat-lying tabular impact melt sheet (Grieve, Stoffler and Deutsch 1991). Alternatively, the Sudbury Igneous Complex may have originally had an inverted funnel shape (Shanks and Schwerdtner 1991b).

A post-Penokean magmatic event of granitic plutonism (~1750 Ma; Davidson and van Breemen 1994) affected the southern part of the Sudbury Structure. Subsequently, at approximately 1450 Ma (Shanks and Schwerdtner 1991a; Fueten and Redmond 1997), the Sudbury region underwent another orogenic event that involved southeast-over-northwest ductile thrusting.

The South Range shear zone is 50 km long by 7 km wide and affects the Onaping Formation, to the north, and the Sudbury Igneous Complex in the South Range of the Sudbury Structure. The South Range shear zone is bounded in the north by folded rocks of the Whitewater Group, which includes the Onaping, Onwatin and the Chelmsford formations; and, to the south, by virtually undeformed layered rocks of the Sudbury Igneous Complex (Shanks and Schwerdtner 1991a). The South Range shear zone is expressed by rocks that are foliated and lineated. The structure accommodated net thrust displacement of approximately 8 km (Shanks and Schwerdtner 1991a). In this report, we suggest that the earliest deformation on the South Range shear zone may have occurred during the final stages of solidification of the Sudbury Igneous Complex.

The Sudbury olivine diabase dike swarm was emplaced at 1238±4 Ma (Krogh et al. 1987).

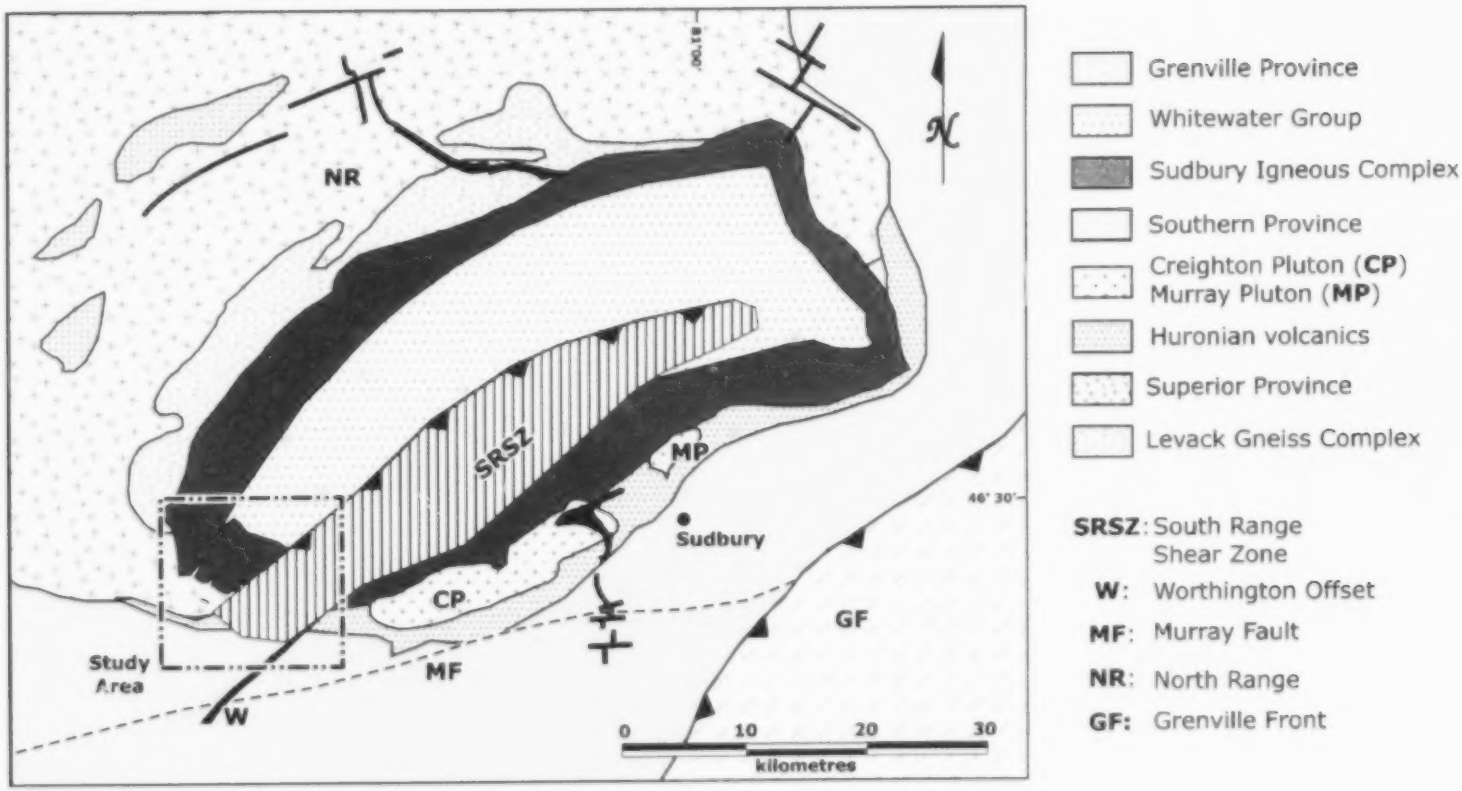

Figure 2. General geology of the Sudbury Basin (from Scott and Benn 2001).

The last orogenic event that affected the Sudbury Structure was the Grenville Orogeny (1070 to 1000 Ma) (e.g., Zolnai, Price and Helmstaedt 1984). Within the Sudbury Structure, the Grenvillian Orogeny is characterized by dominantly brittle deformation. This deformation event also reactivated the east-northeast-striking Murray fault zone, resulting in right-lateral displacements (Card 1968).

Results of the Geological Study

MAJOR ROCK TYPES OF THE SUDBURY IGNEOUS COMPLEX

Figure 3 (back pocket) summarizes the results of the geological mapping component of the project, including the distribution of major rock types and structural measurements. Much of the detailed mapping and the examination of drill cores were concentrated within the Sudbury Igneous Complex, which is the focus of this section.

A total of 80 thin sections were prepared from oriented hand specimens collected during mapping, and 31 thin sections were prepared from representative drill-core samples. The thin sections were studied in order to complete the geological mapping and to document deformation at the microscopic scale. Previous workers have already described the petrology of the Sudbury Igneous Complex in the South and North ranges of the Sudbury Structure (Naldrett et al. 1970; Naldrett and Hewins 1984; Therriault 2001; Therriault, Fowler and Grieve 2002). Our petrographic identification of rock types was accomplished by texture and mineral composition analyses and by comparison with previously published lithologic and petrographic descriptions (e.g., Naldrett and Hewins 1984).

During the cooling of the Sudbury Igneous Complex, an inclusion-rich layer referred to as the sublayer, formed between the footwall rocks and the lowermost norite of the complex (Morrison, Jago and White 1992). Outcrops of sublayer composition are mapped close to the Victoria Mine and to the Sultana Mine (*see* Figures 1 and 3). The sublayer lithology also crops out discontinuously at the contact between the Sudbury Igneous Complex and the footwall rocks. The sublayer matrix is a fine- to coarse-grained, norite to gabbro. A wide variety of xenoliths are included in the matrix and were derived from the adjacent footwall (Pattison 1979). Xenolith size ranges from a few millimetres to 20 cm. Within the South Range shear zone, the xenoliths are strongly sheared and stretched in only one direction. The "cigar shape" of deformed xenoliths indicates that the finite strain is of a contractional nature (Photo 1). A gradational contact is observed between the sublayer and the overlying norite.

Norite crops out on the roadside north of the Chicago Mine and south of Fairbank Lake; north of the Victoria Mine and south of Skill Lake; and southwest of Cameron Lake. The norite matrix is medium- to coarse-grained, dark green to black, and consists of cumulate plagioclase and enstatite crystals embedded within intercumulate quartz, augite, magnetite and ilmenite; the norite also locally contains amphibole and biotite (Naldrett and Hewins 1984). The principal minerals are plagioclase (up to 50%), augite (<2%), orthopyroxene (enstatite) (10%), biotite and primary amphibole (ferro- and magnesio-hornblende) (5%). The lower part of the norite is quartz-rich (5 to 20% of the volume) (Naldrett et al. 1970; Naldrett and Hewins 1984), whereas the upper part contains less than 5% quartz. In the South Range, the norite contains mafic layers that are characterized by small feldspar crystals (Photo 2) and more felsic layers (Photo 3) characterized by feldspar crystals that are twice as big as crystals in the more mafic units. A gradational contact is observed between the norite and the overlying quartz gabbro unit (Therriault 2001).

Photo 1. Photograph of a hand specimen of sublayer composition collected at the Victoria mine. Clasts record a constrictive deformation.

In hand specimen, the quartz gabbro strongly resembles the norite, but it is characterized by a greater abundance of quartz. The quartz gabbro is dark grey to black, coarse-grained and composed of plagioclase (40%), augite (5%), hornblende (15%) and biotite (20%). Micrographic intergrowths of quartz and plagioclase are common (up to 20% of the interstitial phase). Plagioclase crystals are subhedral to euhedral prismatic, lath shaped and 0.5 to 3.0 mm in length. Clinopyroxene (augite) crystals are subhedral to anhedral prismatic, lath shaped and 0.1 to 3.0 mm in length. Quartz gabbro crops out southwest of Cameron Lake and south of Skill Lake. The contact between the quartz gabbro and the overlying granophyre is also gradational (Therriault 2001).

Granophyre crops out around Fairbank, Cameron and Skill lakes. Most outcrops of granophyre are strongly foliated and lineated, as they lie within the South Range shear zone. The granophyre is coarse grained, compositionally heterogeneous and apparently unlayered. It is composed mainly of micrographic and granophyric intergrowths (*see* Photo 3). The lower part of the granophyre is light pink and coarse grained with a cumulate texture and abundant micrographic and granophyric intergrowths. Epidote (5 to 10%) and primary biotite crystals are also present in the lower granophyre. The middle part of the granophyre is grey and characterized by an increase in chlorite content (10 to 15%), primary biotite and oxide minerals (Therriault 2001). The upper part of the granophyre is medium grained and pink and contains very abundant micrographic and granophyric intergrowths (60 to 65%). The contact between the granophyre and the overlying Onaping Formation is not easily identifiable. In some places, the Onaping Formation has apparently sunk into the granophyre, and in other places the granophyre is found surrounded by Onaping Formation (Naldrett 1984).

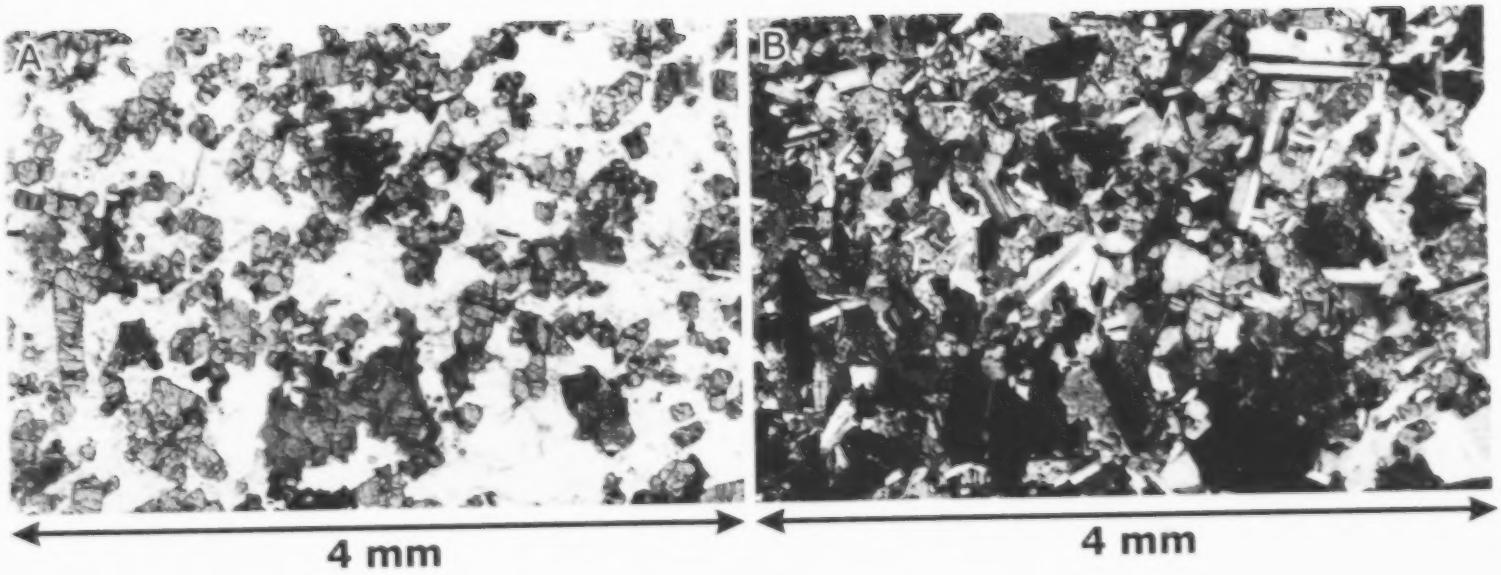

Photo 2. Photomicrograph of a thin section of sample 02AD13, a more mafic norite, taken without (A) and with (B) crossed polars. Field of view in each photo is 4 mm wide.

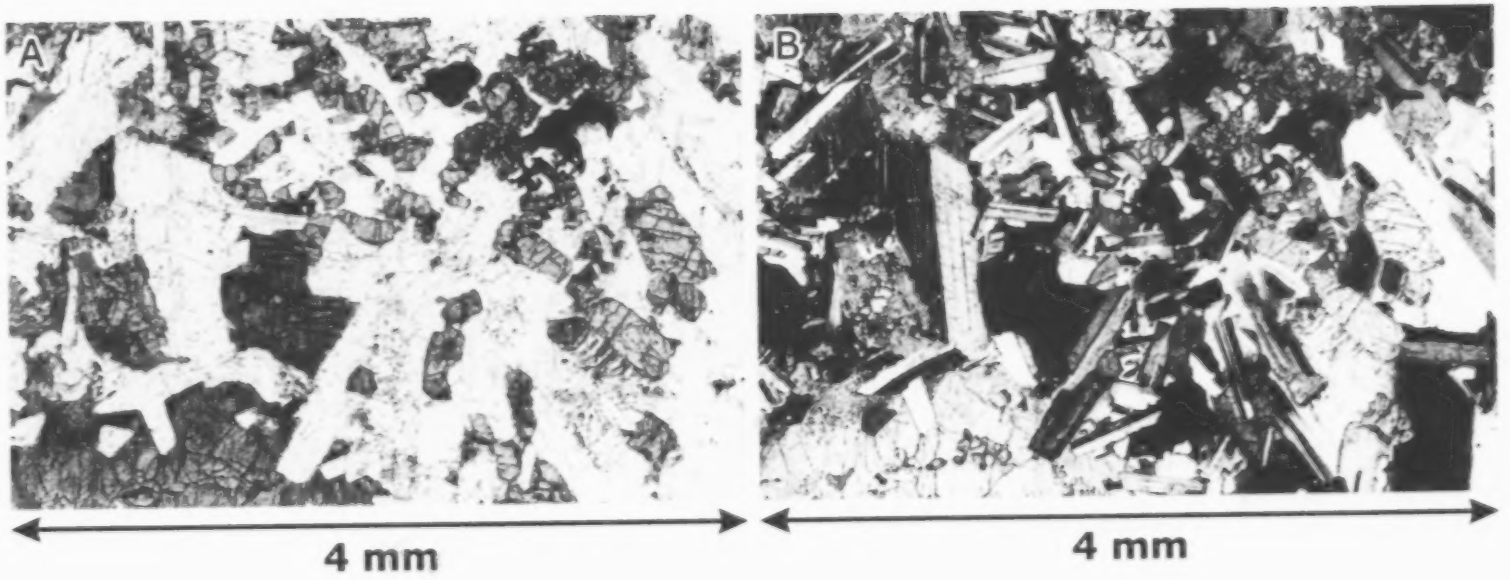

Photo 3. Photomicrograph of a thin section of sample 02AD27, a more felsic norite, taken without (A) and with (B) crossed polars. Field of view in each photo is 4 mm wide.

STRUCTURAL GEOLOGY

Pre-impact Structures

The only pre-impact structures unequivocally recognized within the study area are folds associated with the Sudbury to Espanola fold belt of the Southern Province. These structures do not seem to have strongly influenced the present structural configuration of the study area.

Another fundamental feature of the Sudbury Structure that may be indicative of the presence of pre-Sudbury event faults in the Sudbury Basin, are the angular boundaries of the Sudbury Igneous Complex, at both of its northeastern and southeastern corners (*see* Figure 2). In the study area, the map pattern of the original boundaries of the Sudbury Igneous Complex have been strongly modified by subsequent deformation and it is not possible, based on existing data, to determine if the southwestern corner of the Sudbury Igneous Complex was also originally angular, as are the northeastern and southeastern corners. It is our hypothesis that the angular corners of the Sudbury Igneous Complex indicate that the melt body was bounded by pre-existing fault sets in the footwall rocks. That hypothesis will be discussed further on in this report, in the section on "Three-dimensional modelling".

Impact-Related Structures

SHATTER CONES

Shatter cones are distributed in a 20 km diameter ring around the Sudbury Igneous Complex (Gibson and Spray 1998). Shatter cones are shock-induced structures generated by a large, hypervelocity impact (Dietz 1964). The presence of shatter cones in the Sudbury Structure is one of the prime geological elements that has led many workers to interpret the origin of the Sudbury Igneous Complex, to be the result of a meteorite impact.

Shatter cones are present in the southeast corner of the study area (Figure 4). They are particularly well exposed on the eastern side of the road that leads to the Lockerby Mine. There, the shatter cones occur within the McKim Formation of the lower Huronian Supergroup. The shatter cones are presently oriented with vertical axes and with striations that converge upward (Photo 4a).

Sagy, Reches and Fineberg (2002) studied the process of shatter cone formation at the Vredefort impact site, in the Republic of South Africa. In particular, they studied variation in the aperture angles defined by shatter cones at various locations with respect to the centre of the impact structure. The aperture angle of a shatter cone is defined as the angle subtended by the striations (Photo 4b). Sagy, Reches and Fineberg (2002) documented a systematic increase of the shatter cone aperture angles with increasing distance from the centre of the impact structure.

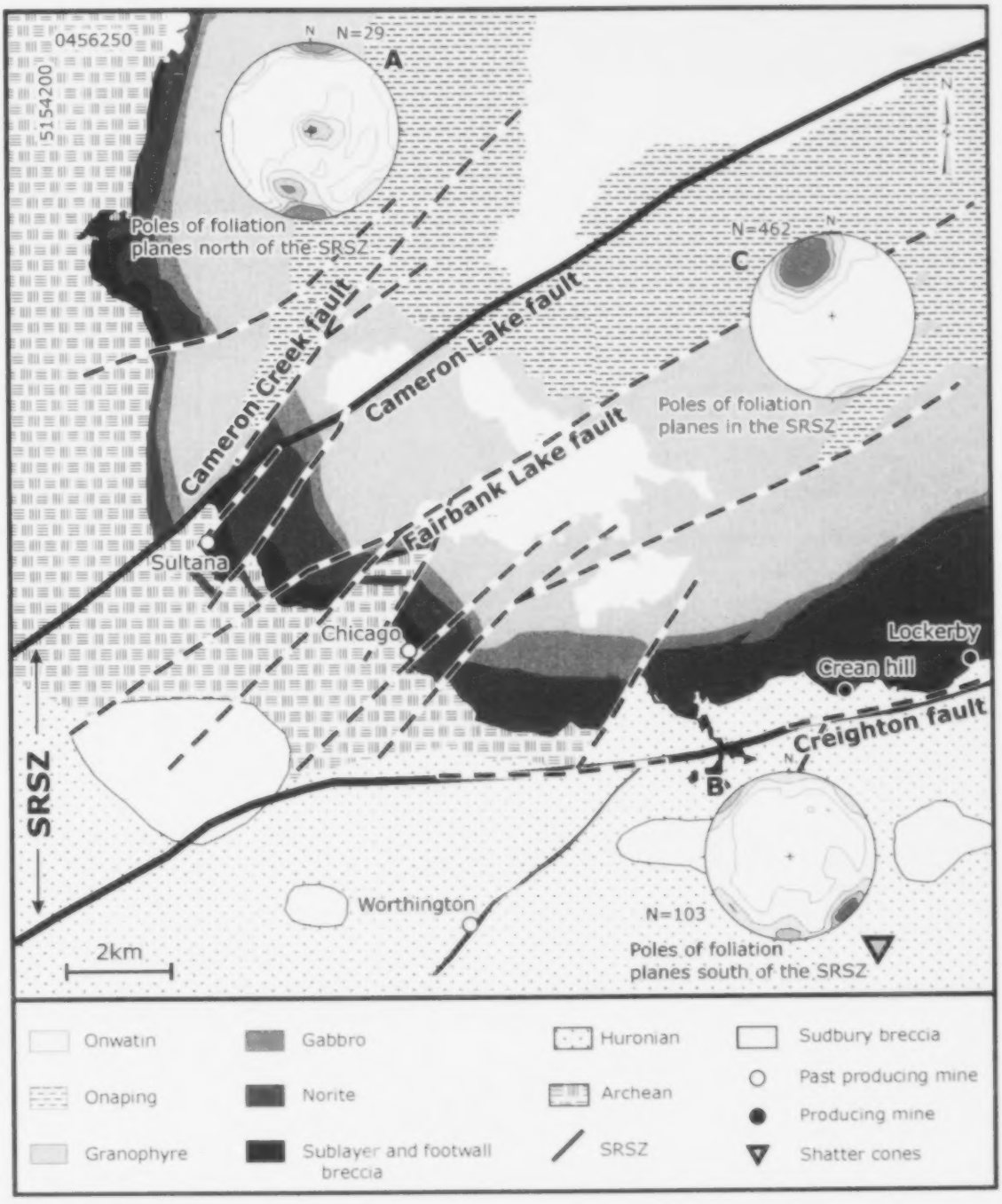

Figure 4. Location of shatter cones and the limits of the South Range shear zone (SRSZ) in the study area. The equal-area projections display the orientations of foliation planes measured to the north (A) and south (B) of the SRSZ, and within the SRSZ (C). The white areas indicate abundant Sudbury breccias.

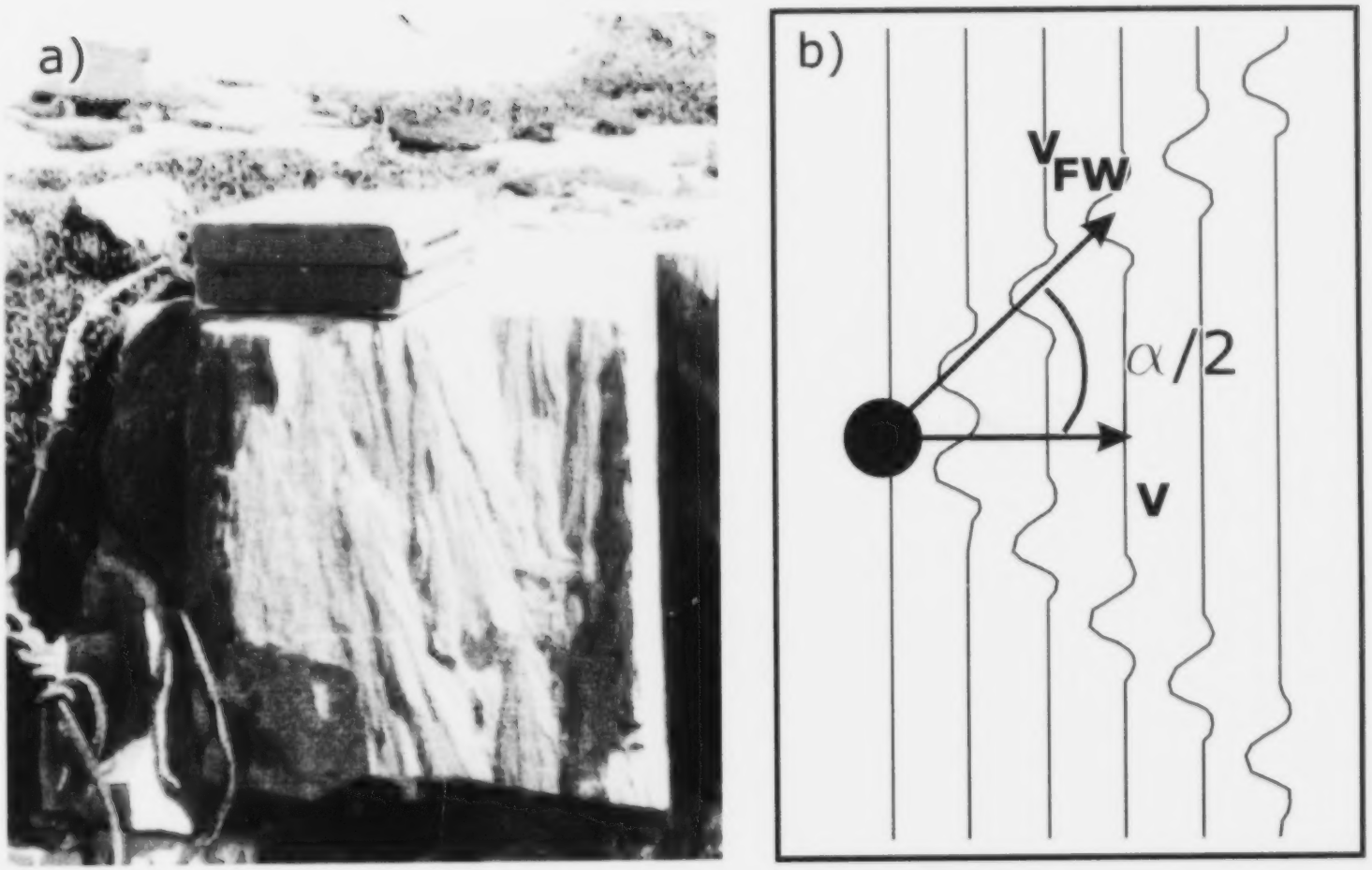

Photo 4. a) Photograph of shatter cones in the road cut at the junction of Highway 658 and the road going to Lockerby Mine (compass for scale). b) the aperture angle of shatter cone (a), based on Sagy, Reches and Fineberg (2002). α = aperture angle; V = propagation velocity of the fracture front; V_{FW} = propagation velocity of the fracture front wave.

The Sudbury and Vredefort structures are similar in size and both are characterized by the presence of impact melt bodies (Melosh 1989). Therefore, we thought it useful to plot the aperture angles of the shatter cones in the study area on the plot of Sagy, Reches and Fineberg (2002) (Figure 5). Measurement of the aperture angles of 13 shatter cones in the study area give a mean value of 46.62 (±11.76) degrees. According to Figure 5, shatter cones in the southeast part of the study area would have been formed at a distance of roughly 35 km (±5 km) from the centre of the impact.

Taking into account the proposed 8 km of shortening in the South Range of the Sudbury Structure (Shanks and Schwerdtner 1991a), the centre of the impact would be located at 30 km from the measurement site (Figure 6). Of course, this estimate is based on measurements of shatter cone aperture angles from a single site and further determinations from other parts of the Sudbury Structure would be required in order to more precisely locate the centre of the impact.

SUDBURY BRECCIA

Sudbury Breccia is also present in the study area. It consists of clasts of Huronian Supergroup rocks hosted within a dark fine-grained matrix. The colour of the breccia matrix may be lighter where the breccia occurs in arkosic rocks (Elliott Lake Group). The outcrops of Sudbury Breccia are interpreted to be part of the western extension of the South Range breccia belt, studied to the east of the study area by Scott and Spray (1999, 2000).

Most outcrops in the study area allow observations to be made only on a horizontal surface. In a horizontal plane, the clasts range from centimetre to decametre in size (Photo 5a). They do not display a preferred orientation in the horizontal plane. On one outcrop, observations on a vertical plane indicate that the breccia clasts are strongly elongated and plunge steeply to the north (Photo 5b). The clast shapes indicate that the finite strain state of the breccia is constrictional, i.e., the finite strain ellipsoid is cigar-shaped. A constrictional finite strain state is also characteristic in the South Range breccia belt where it is more thoroughly studied, to the east of the study area (Scott and Spray 1999, 2000). The elongate clasts in Photo 5b are in an outcrop that is outside of the boundaries of the South Range shear zone and therefore they are attributed to deformation associated with emplacement of the Sudbury Breccia.

Post-impact Ductile Structures

SOUTH RANGE SHEAR ZONE (SRSZ)

Much of the work focussed on post-impact ductile deformation, which in the study area is expressed mainly within the South Range shear zone. To the east of the present study area, the South Range shear zone is at least 80 km long and up to 10 km wide (Shanks and Schwerdtner 1991a). The South Range shear zone is bounded to the north by the Fairbank Lake Fault and folded rocks of the Whitewater Group, which include the Onaping, Onwatin and Chelmsford formations; and to the south by unstrained rocks of the Sudbury Igneous Complex (Shanks and Schwerdtner 1991a). To the east of the study area, the South Range shear zone may have accommodated a net thrust displacement of approximately 8 km (Shanks and Schwerdtner 1991a).

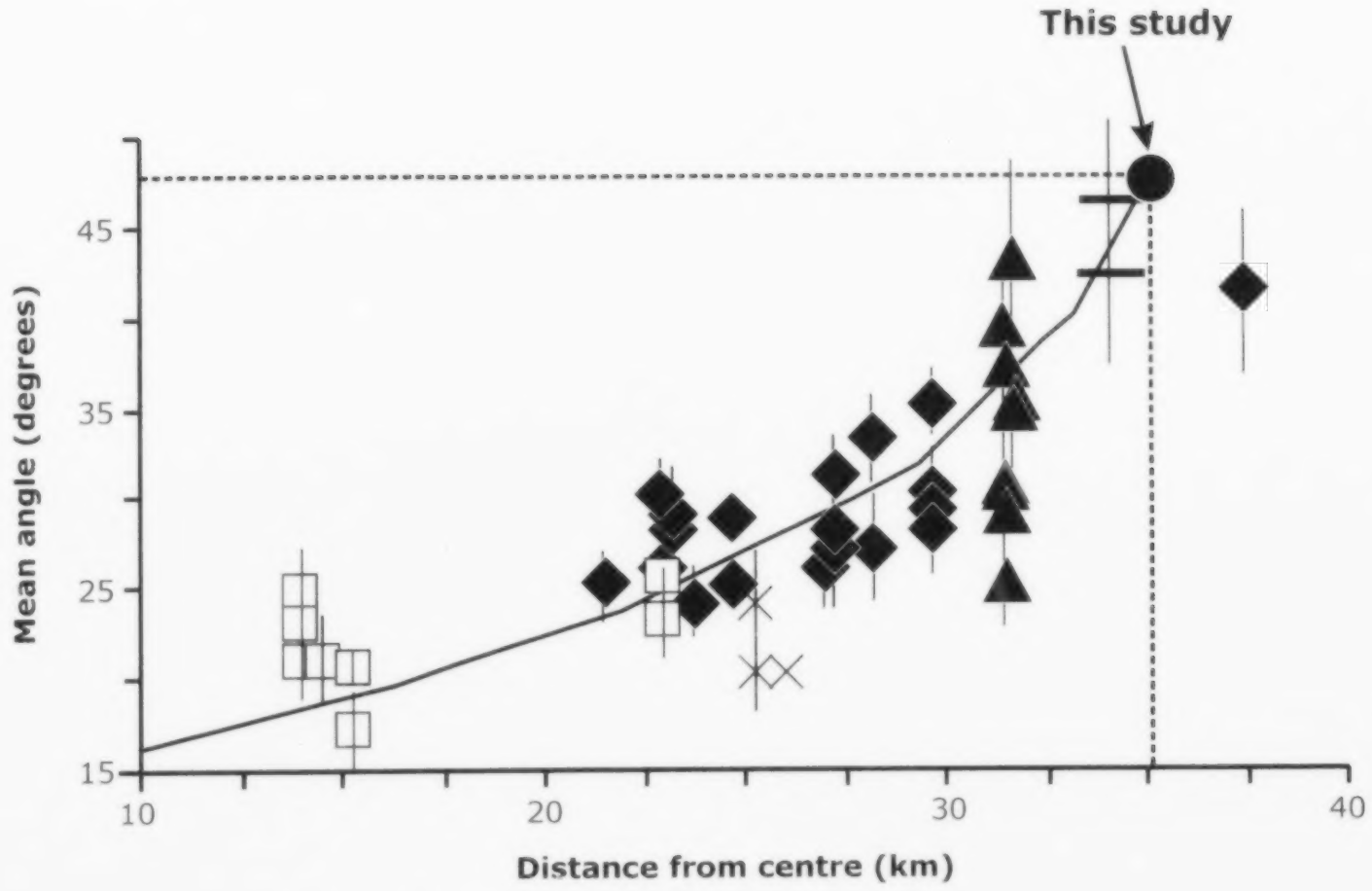

Figure 5. Mean aperture angle determined in the study area on a plot using data from Vredefort Structure.

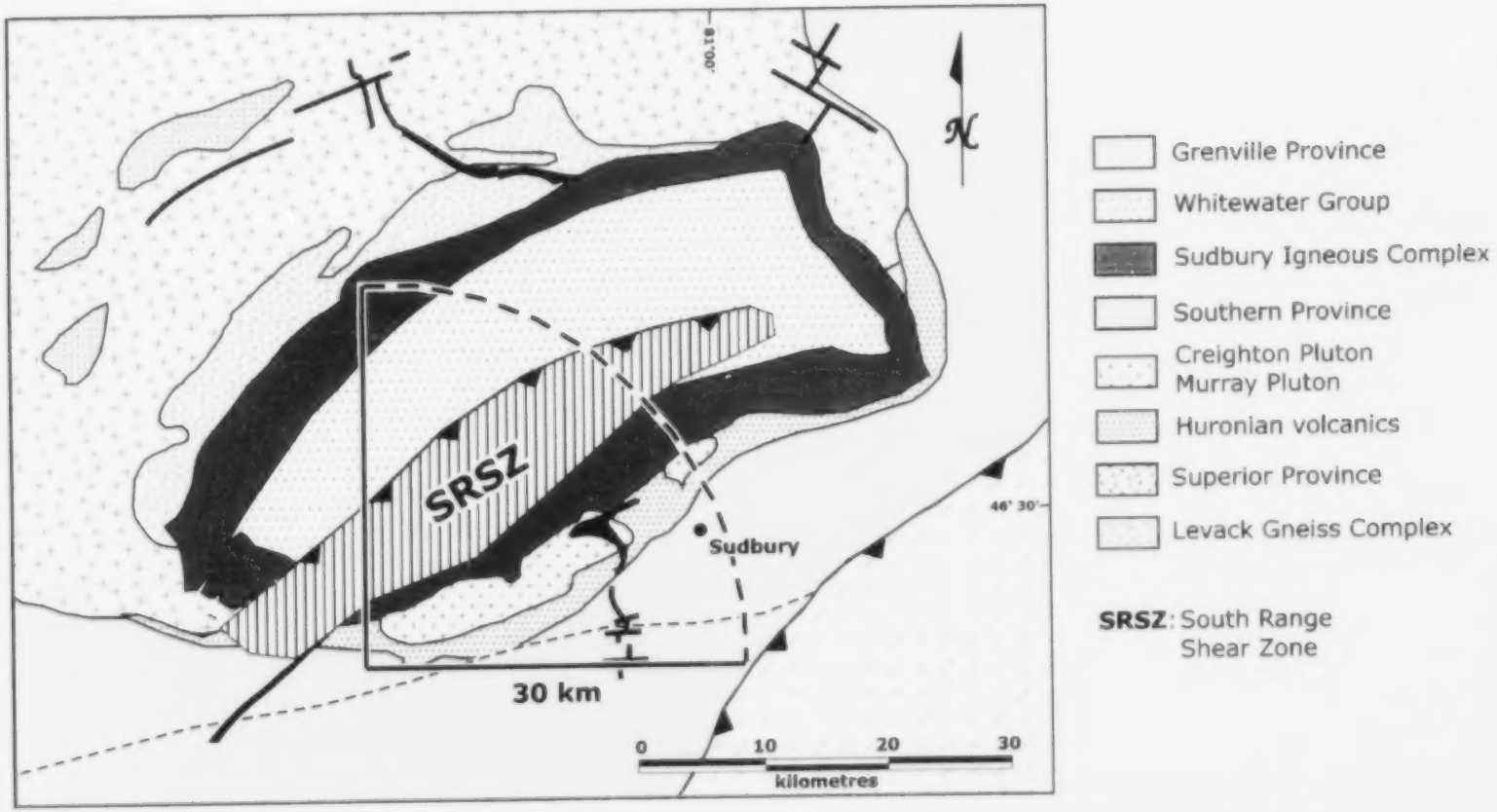

Figure 6. Attempt to locate the centre of the impact. The measurement site is about 30 km away from the centre of the impact (see text for more details). The centre of the impact would lie on the arc indicated by the heavy dashed line. The mid-point of this arc, which may approximate the centre of the impact, lies roughly 4 km north of the town of Balfour.

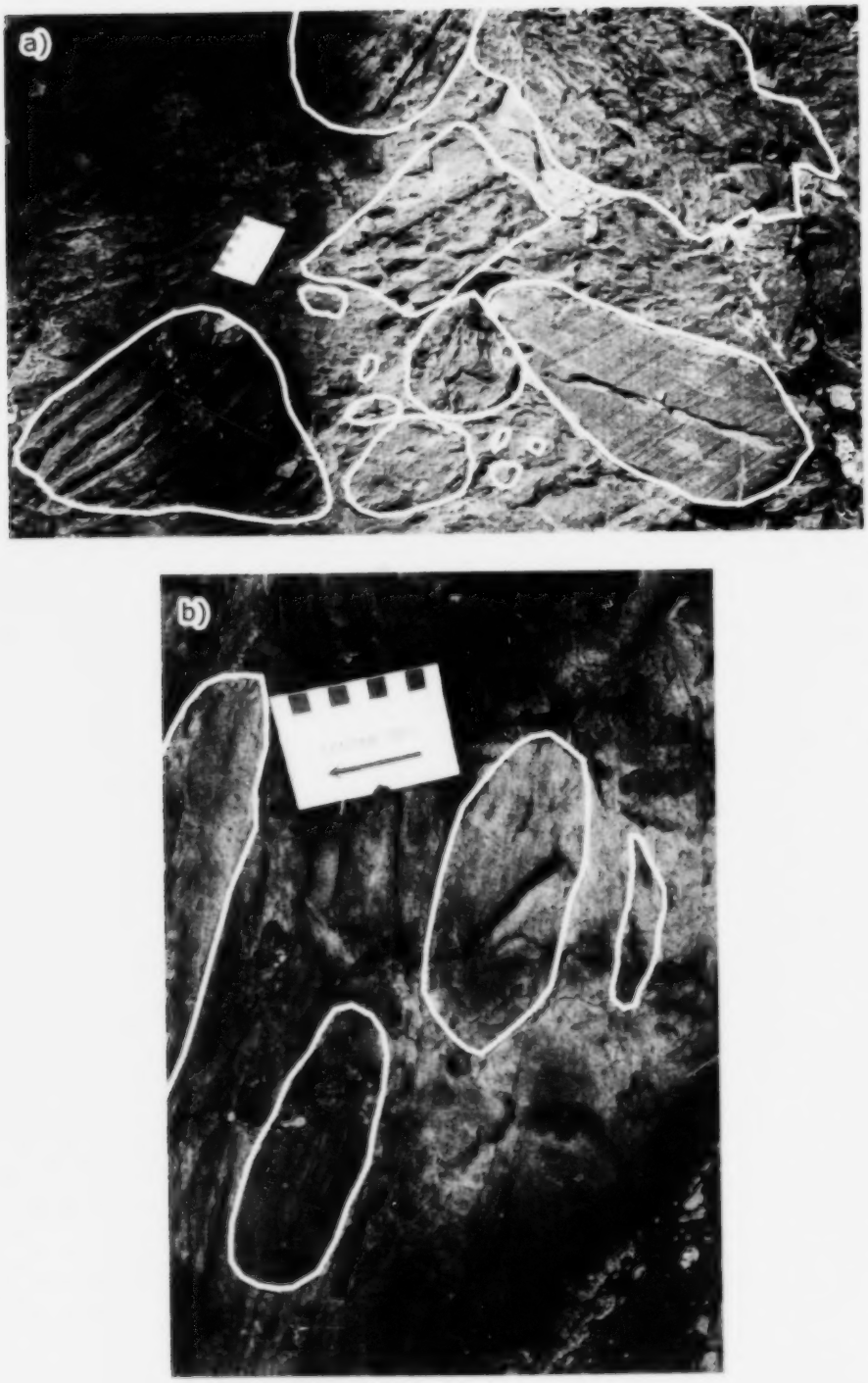

Photo 5. Photographs of a) Huronian clasts in Sudbury Breccia observed on a horizontal surface, and b) on a vertical surface, looking to the east.

Within the study area, strong ductile shearing related to the South Range shear zone affected parts of the Onaping Formation, the southern part of the Sudbury Igneous Complex and the footwall of the Sudbury Igneous Complex (*see* Figure 4). The South Range shear zone is characterized by penetratively foliated and lineated rocks. Outcrops inside the South Range shear zone display foliation planes that strike on average 60° and that dip on average 60° to the southeast (*see* Figure 4); notably, this average strike is similar to the trend of major faults in the western Sudbury basin (*see* Figure 4).

The ductile shearing within the South Range shear zone has overprinted any pre-existing structures. The intensity of the deformation resulted in the isoclinal folding of abundant quartz veins and transposition of many veins parallel to the foliation. In the Onaping Formation, numerous deformed clasts also allow for interpretation of the sense of shear. For instance, Photo 6 shows a vertical outcrop surface in the Onaping Formation where the asymmetrical wings on a sheared σ-type clast indicates a south-over-north displacement associated with the development of the foliation. Extension lineations generally rake very steeply to the northeast of the dip line of the foliation; hence we interpret the South Range shear zone as a mainly reverse-sense shear zone with a subordinate dextral component. The dextral component of shear is confirmed by documentation of quartz veins that have sigmoidal shapes and are counterclockwise-oblique to the mylonitic foliation (Photo 7). The mainly reverse shear sense registered in the South Range shear zone indicates that, northwest of Fairbank Lake, the granophyre unit of the Sudbury Igneous Complex *is thrust over* the Onaping Formation. Study of thin sections from the granophyre that contain S–C microfabrics confirm the sense of shear inferred from field observations (Dubois and Benn 2003).

Figure 7 presents measurements of extension lineations in outcrops where the sense of shear could be determined in the field or in thin section. In 21 outcrops, a predominant reverse (south over north) sense of displacement was determined. Four outcrops revealed an apparent normal sense of displacement (*see* Figure 7). The outcrops displaying a normal sense of shear are located in the Onaping Formation and also in the footwall rocks. The significance of the normal sense of shear determined at these 4 outcrops is not entirely clear and the data set of normal shear sense indicators is severely limited; however, it is conceivable that some ductile normal faulting may have occurred within the South Range shear zone either early or late in its kinematic evolution. Alternatively, the few normal sense indicators documented within the South Range shear zone may be due to locally heterogeneous shearing and possibly to shearing on isoclinal, overturned limbs of folds. We propose that more detailed studies of the kinematic history of the South Range shear zone may be needed, especially in the Onaping Formation, in order to determine if the shear zone may have some history of normal displacements. As will be discussed in the section on "Three-dimensional modelling", structural repetition within the South Range shear zone strongly suggests the presence of an early period of normal faulting in the Sudbury Igneous Complex and in its footwall.

In some outcrops within the South Range shear zone, a strong constrictional fabric is observed, i.e., clasts are highly elongated, defining a strong lineation, but the foliation is poorly developed or absent. This observation is important for mappers to consider because on horizontal outcrop surfaces, which are at a high angle to the extension lineations, the rocks with highly constrictive fabrics appear to be undeformed. The constrictional fabric may be the result of a partitioning of deformation into steeply south-dipping shear zones (where structures record non-coaxial shearing, as described above) that bound rock volumes wherein strain is recorded by systems of vertical, anastomosing shear zones that suggest a bulk pure shear and a constrictional finite strain. The northwest transport of the rocks in the hanging wall of the South Range shear zone would have been accommodated by the non-coaxial shear zones, whereas much of the South Range shear zone may have been affected by a bulk horizontal shortening accompanied by vertical extrusion that gave rise to the vertical anastomosing shear zones. Interestingly, some sulphide mineralization seems to have a positive spatial relationship with the anastomosing vertical shear zones, suggesting possible remobilization of sulphide mineralization during post-Sudbury impact deformation.

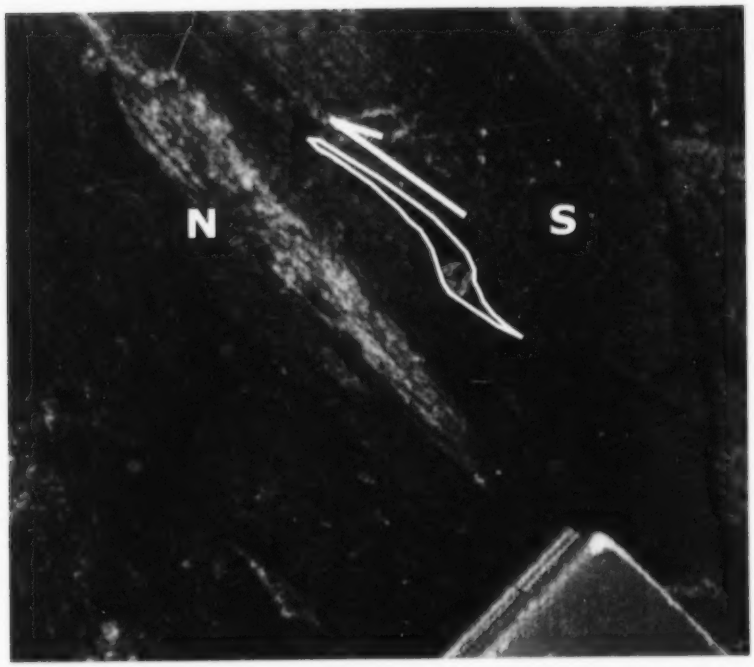

Photo 6. A deformed s-type clast in the Onaping Formation, observed on a vertical plane. The reverse (south over north) sense of shear in the SRSZ is indicated by the sigmoidal shape of the wings attached to the clast (outlined in white). Edge of compass for scale.

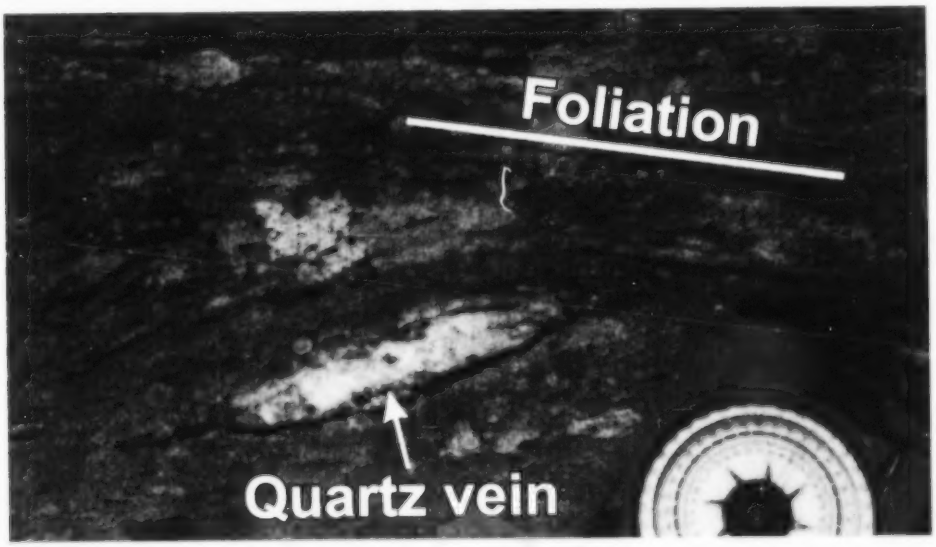

Photo 7. Sigmoidal boudinaged quartz vein, counterclockwise-oblique to the foliation plane, indicating a dextral sense of shear. Compass for scale.

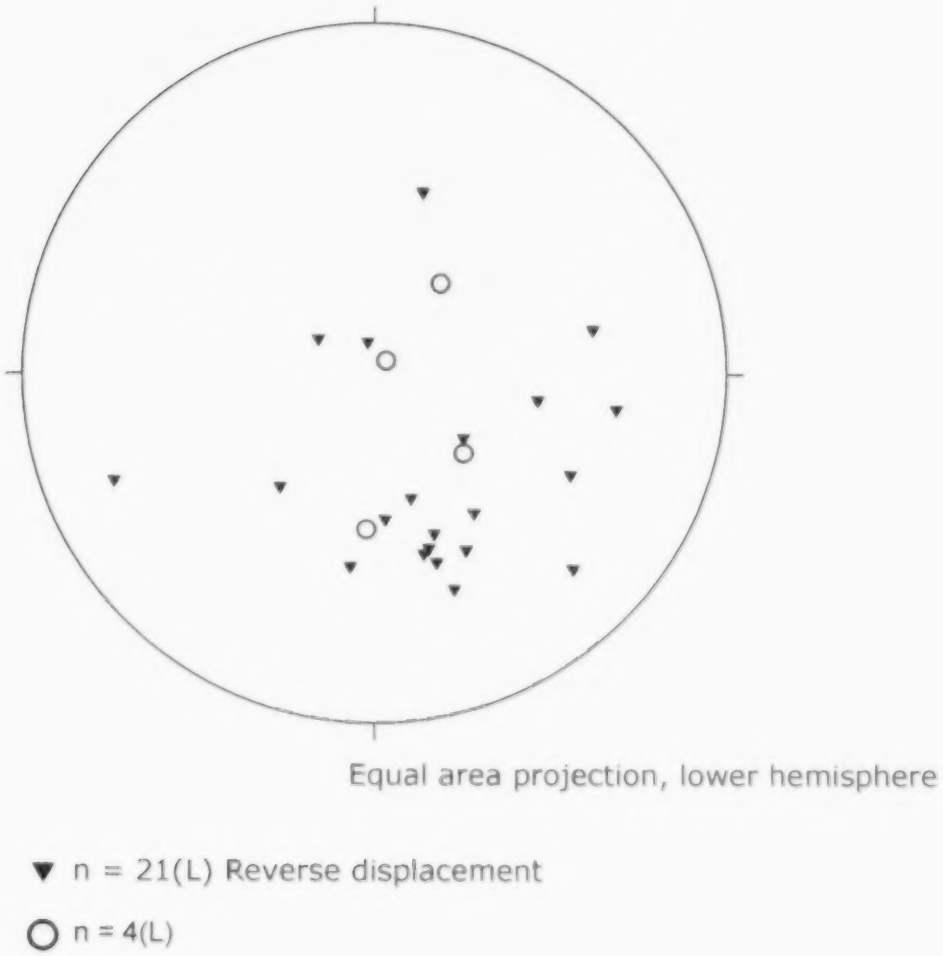

Figure 7. Lineations (L) measured on foliation planes and displayed onto a stereonet, equal-area lower hemisphere projection. Triangles refer to a reverse displacement on a fault plane and circles to a normal displacement.

The boundaries of the South Range shear zone were determined as the limits of the region where a strong ductile fabric is observed in outcrops. In the study area, the South Range shear zone is bounded to the north by the Cameron Lake and Cameron Creek faults and it is limited by the Creighton fault to the south (*see* Figure 4). For rocks north of the Cameron Creek and Cameron Lake faults, the foliation measurements shown in Figure 4 are from rocks of the Sudbury Igneous Complex and they show a weak east-west preferred orientation. The foliation in that region may record a weak expression of the same deformation event that gave rise to the South Range shear zone (most likely); or, alternatively, it may record an unrelated deformation event.

Footwall Involvement in the South Range Shear Zone

An important observation arising mainly from our investigations of industry diamond-drill core is that footwall rocks are deformed, foliated and lineated, apparently due to the same deformation event that gave rise to the South Range shear zone (Photo 8a and 8b). This interpretation is based on the parallelism between penetrative ductile fabrics in rocks of the Sudbury Igneous Complex and in rocks of the footwall, as observed in several diamond-drill cores (*see* Photo 8a and 8b).

There are two important consequences of the footwall involvement in the South Range shear zone. First, it must now be realized that some potential mineral deposits in the footwall rocks may have been affected by strong, ductile deformation associated with the South Range shear zone. Second, thrusting on the South Range shear zone was responsible, at least in part, for structural repetition of the Sudbury Igneous Complex and the footwall rocks, as documented in several diamond-drill cores. The origin and interpretation of the structural repetition is investigated further in the section on "Three-dimensional modelling".

Age of the South Range Shear Zone

In the norite units in diamond-drill cores, flattened and stretched leucocratic pockets commonly mark the foliation plane (*see* Photo 8a). In thin section, we have observed that the leucocratic pockets consist of small euhedral crystals of igneous plagioclase feldspar that are randomly oriented (Photos 9 and 10). This suggests that the leucocratic pockets were actually melt pockets that were deformed prior to the crystallization of the feldspar within them. The foliation defined by the deformed leucocratic pockets is parallel to the ductile South Range shear zone fabric documented in drill cores and in the field. Hence we interpret that some residual melt must have remained in the norite during the early stages of deformation related to the South Range shear zone. Based on the reasonable assumption that the Sudbury Igneous Complex would have fully solidified within a few million years following the impact event, and on the observation of the deformed leucocratic pockets, we can interpret that the South Range shear zone was active during the few million years following the meteorite impact and the formation of the impact melt body.

POST-SOUTH RANGE SHEAR ZONE DUCTILE DEFORMATION

Post-South Range shear zone deformation was documented at only one location during mapping, where it is expressed as a crenulation of the South Range shear zone foliation. Photo 11 shows an outcrop close to the Victoria Mine. There, the South Range shear zone foliation strikes 60° and it is deformed by a crenulation striking 110° to 135° (*see* Photo 11). At this outcrop, we interpret that the crenulation may record late sinistral movements on nearby faults. Crenulations such as shown in Photo 11 are only documented at the mesoscopic-scale, however, future workers should consider that such structures may also occur at larger scales.

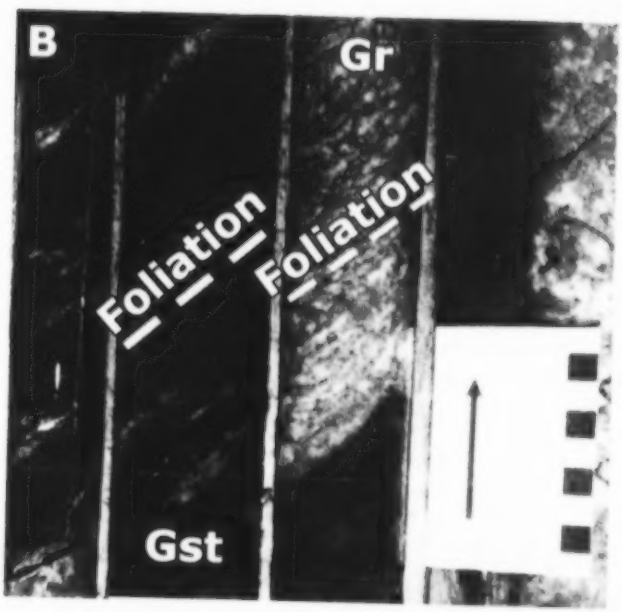

Photo 8. Foliation related to thrusting on the South Range shear zone, observed in core from one diamond drill hole. A) Foliated sublayer norite (Sln). B) Foliation in the footwall rocks, here composed of strongly deformed Neoarchean granite (Gr) and greenstone (Gst) of Superior Province. The arrow on the scale card points to the top of the almost vertical drill hole. The foliation dip is 50° to core axis. The core axis is vertical. Note that the angle between foliation and core axis is similar in all three rock units.

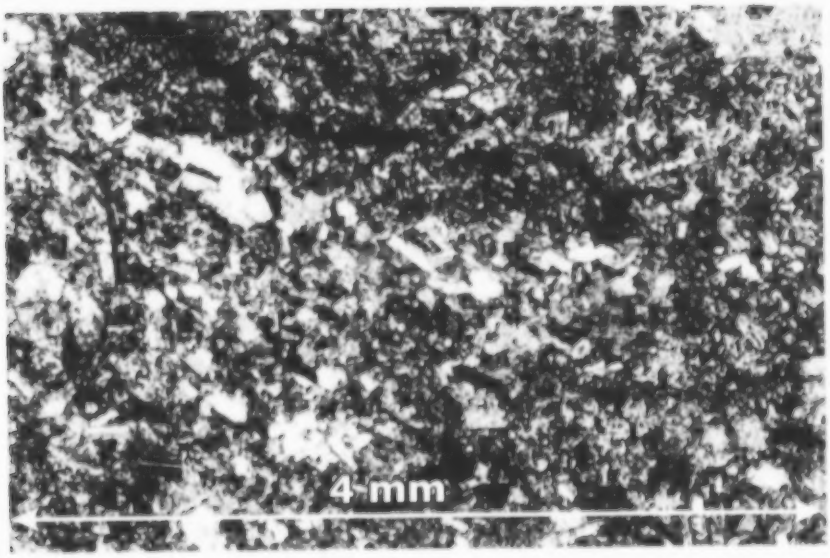

Photo 9. Photomicrograph of a thin section of sample 02AD35, a metamorphosed norite, taken without crossed polars. Field of view is 4 mm wide.

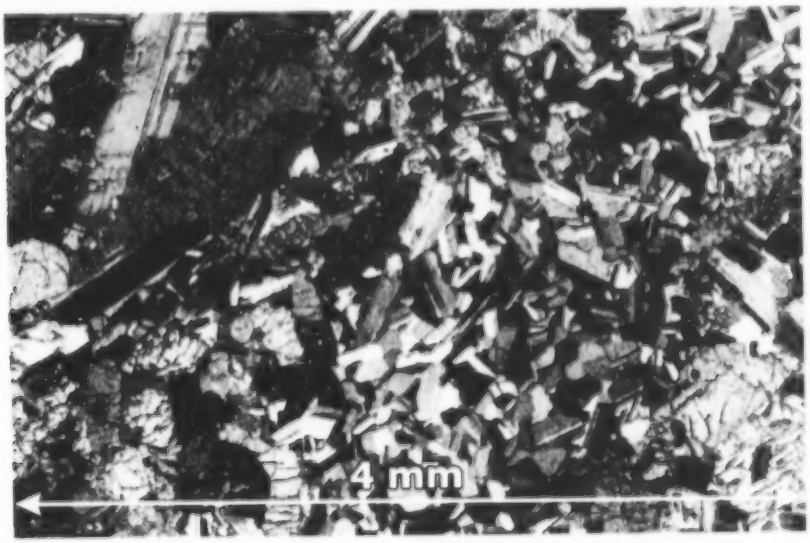

Photo 10. Photomicrograph of a thin section of sample 02AD29, inside of a felsic pocket observed on Photo 9, taken without crossed polars. Field of view is 4 mm wide.

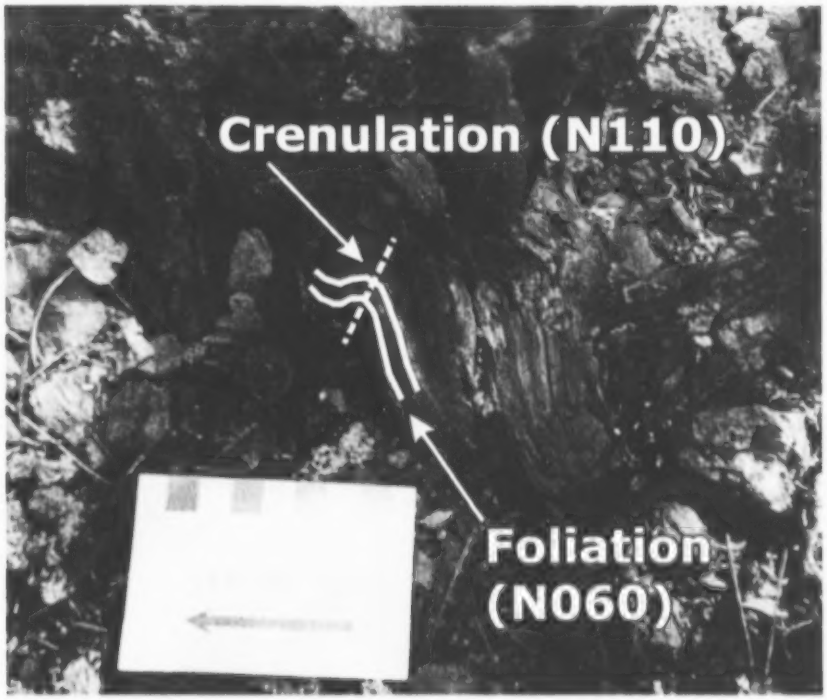

Photo 11. Crenulation of S_1 foliation planes in sulphide-rich rock, in the vicinity of the Victoria Mine. The arrow on the scale card points north.

Post-impact Brittle Structures

Outcrop-scale brittle faults were studied in detail and 5 structural domains were established based on characteristic fault populations. The domains are: 1) south of Mosquito Lake; 2) the area around Cameron Lake; 3) and 4) 2 areas around the western part of Fairbank Lake: north and south of the Fairbank Lake fault; and 5) the area surrounding Skill Lake (Figure 8). Together, the 5 domains represent a section perpendicular to the Fairbank Lake fault, the major fault in the study area.

Brittle faulting is ubiquitous in the study area. The brittle faults can be grouped into 3 main orientations: north-northeast-, northeast- and southeast-striking. All 3 groups are present in the 5 areas that were studied in detail; however, it appears that any one of the groups may be dominant in each area. It is likely that, in the strongly foliated rocks near the Fairbank Lake fault, the predominance of northeast-striking faults is related to reactivation of the foliation during brittle faulting. Field observations of slickensides and striations on fault planes indicate that normal, strike-slip and thrust kinematics were accommodated by different faults.

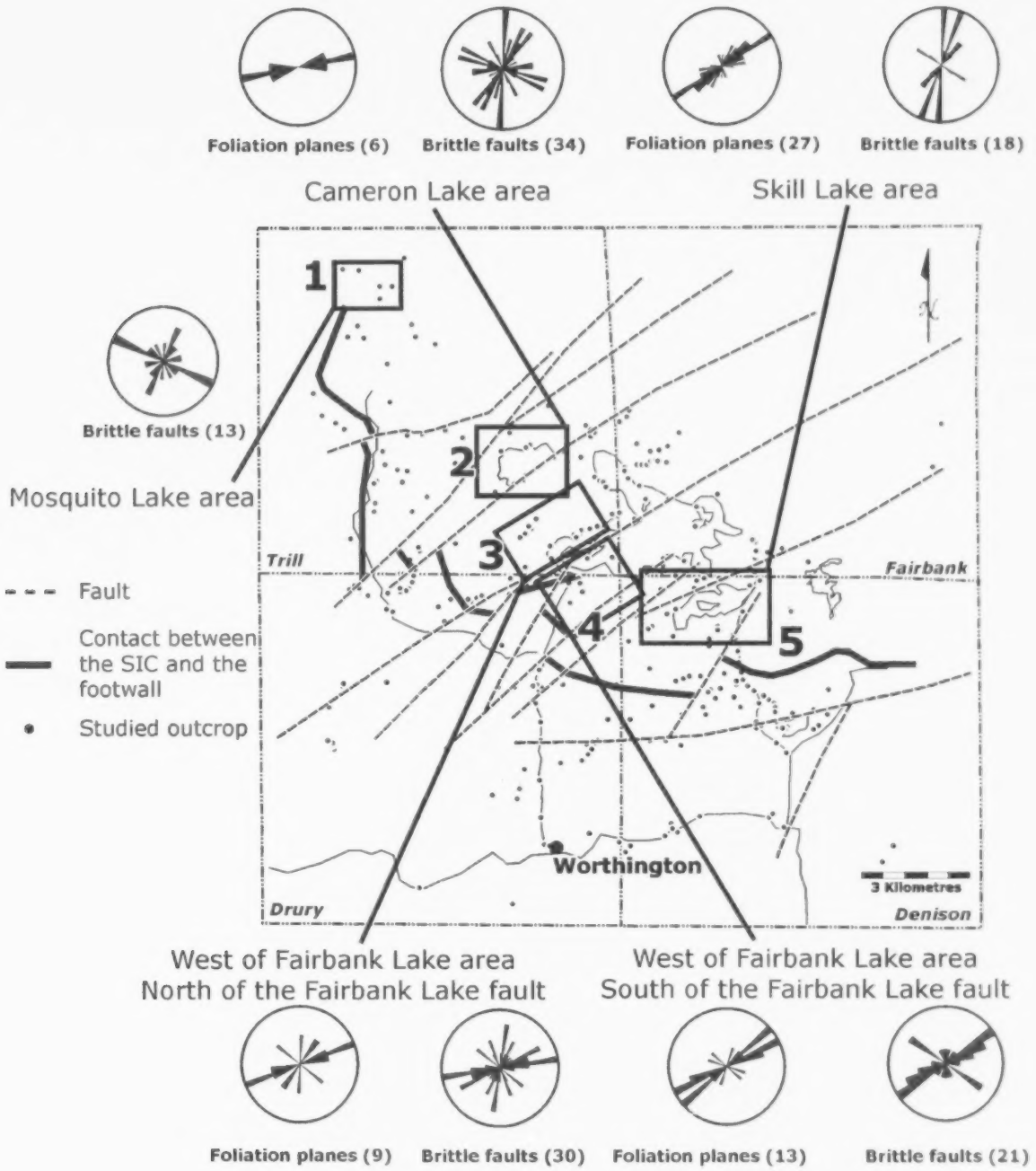

Figure 8. Location of the 5 areas selected for detail structural study.

DOMAIN 1

The Mosquito Lake area is located north of the Fairbank Lake fault and includes the southern part of Mosquito Lake. Seven outcrops were studied where no evidence of ductile deformation was observed. Brittle faults are present and can be divided into 2 main groups based on their orientations: a predominant group of southeast-striking faults and a smaller group of northeast-striking faults. None of the observed faults host sulphide mineralization.

DOMAIN 2

The Cameron Lake area lies along the Cameron Lake fault, a major structure that strikes 055°. Eight outcrops were studied in detail in this area. The rocks are strongly fractured and contain many quartz veins as well as epidote in some places. The penetrative foliation strikes parallel to the Cameron Lake fault. Brittle faults documented in the outcrops can be sorted into 3 main groups according to their orientations: a predominant north-northeast striking group, and subordinate groups of northeast- and southeast-striking faults. All 3 groups have fault breccias preserved within the fault planes. Fault breccia in the southeast-striking faults present a dusty red colour and contain epidote mineralization probably linked with hydrothermal activity.

DOMAIN 3

Ten outcrops were studied in the area west of Fairbank Lake and north of the Fairbank Lake fault. Foliation planes are parallel to the trace of the Fairbank Lake fault and have an average strike of 070°. Many fault planes have developed in foliation planes and have exploited the foliation as a plane of mechanical weakness, however, the predominant orientation of brittle faults is 080°, oblique to the foliation and to the Fairbank Lake fault. The north-northeast-striking faults are the most abundant group, which is similar to the Cameron Lake area. The north-northeast-striking faults present, at some outcrops, quartz mineralization on their fault planes. Only a few fault planes that strike 155° show evidence of a red, dusty coloured alteration.

DOMAIN 4

Eight outcrops were studied in detail south of the Fairbank Lake fault. As in domain 3, the foliation is predominantly parallel to the Fairbank Lake fault (070°). Brittle faults are either northeast- or southeast-striking. Few faults were documented with the north-northeast strike that is common in the other areas described here. In this area, a red, dusty coloured alteration was found only on northeast-striking fault planes.

DOMAIN 5

Seventeen outcrops were studied in the Skill Lake area. The foliation planes are predominantly parallel to the Fairbank Lake fault (070°). Numerous quartz veins were observed within the foliation planes and quartz veins that strike 040°, that is to say oblique to the foliation, are commonly folded. This is possibly due to transposition of the veins during ductile deformation. Brittle faults occur in the following 3 orientations: north-northeast-, northeast- and southeast-striking. Epidote is present on several outcrops and a red, dusty coloured alteration occurs on the north-northeast-striking fault planes.

PALEOSTRESS FIELD CALCULATIONS

Analysis of the stress fields associated with brittle faulting was carried out using software developed by Ramsay and Lisle (2000). The program performs a grid-search method of stress inversion from fault slip data, i.e., fault plane orientation and striations. Results show a northwest maximum (σ_1) compression direction (Figure 9). This suggests that brittle faulting records late northwest-southeast shortening of the Sudbury Basin.

The maximum compression direction during the Grenville Orogeny was east-west (Cowan, Riller and Schwerdtner 1999). Thus, the brittle faulting observed in the study area, which occurred during a period when the maximum compressive stress was oriented northwest-southeast, is not likely related to the Grenville Orogeny. Most likely this brittle phase of shortening of the Sudbury Structure was due to a late phase of the Penokean Orogeny.

Three-Dimensional Modelling

After gathering structural field observations and petrographic information from hand samples and thin sections, we focused on the third dimension (depth) mainly by the incorporation of diamond-drill core observations. Several mining companies possess diamond-drill hole logs for the study area. Inco, Falconbridge Limited and FNX Mining Company allowed us to access some of their drill holes and provided log information. The selected cores are from diamond-drill holes that were collared on lake shores (Fairbank Lake, Ethel Lake and Bass Lake), along the footwall contact of the Sudbury Igneous Complex, and on former mining sites (Chicago Mine, Crean Hill Mine and the Sultan Mine). Drill core data were compiled into CAD drawing files that were used to construct vertical cross-sections in order to constrain three-dimensional models. A software package was then used to test possible three-dimensional kinematic models for the deformation of the western Sudbury Basin that conform to the results of mapping and of drill-core studies.

MODELLING SOFTWARE

The Noddy™ software package was used for the three-dimensional modelling. The software deals with a 3D-block, the size of which can vary from 50 by 50 by 50 m to 9000 by 9000 by 9000 km, which is more than enough to model the study area. This 3D-block is composed of cubic cells of variable size, and the chosen cell size defines the resolution of the model. A cell edge may range from 50 m to 1 km. Geometrical, lithologic and petrophysical characteristics (rock properties) of the rocks were integrated into the models. The modelling process involves choosing a possible pre-deformational configuration for the study area, including its geometrical and compositional makeup and pre-existing structures, and imposing a deformational history on the modelled rock body.

The resulting deformed model may be tested for conformity with geological and geophysical data by 1) generating three-dimensional blocks that can be compared to the known surface and subsurface geology; and 2) by generating geophysical maps from model results using the petrophysical properties of the rocks in the study area (e.g., densities, magnetic properties). Some examples of forward modelling were presented by Dubois and Benn (2003). The software can also generate artificial drill-holes based on the model results.

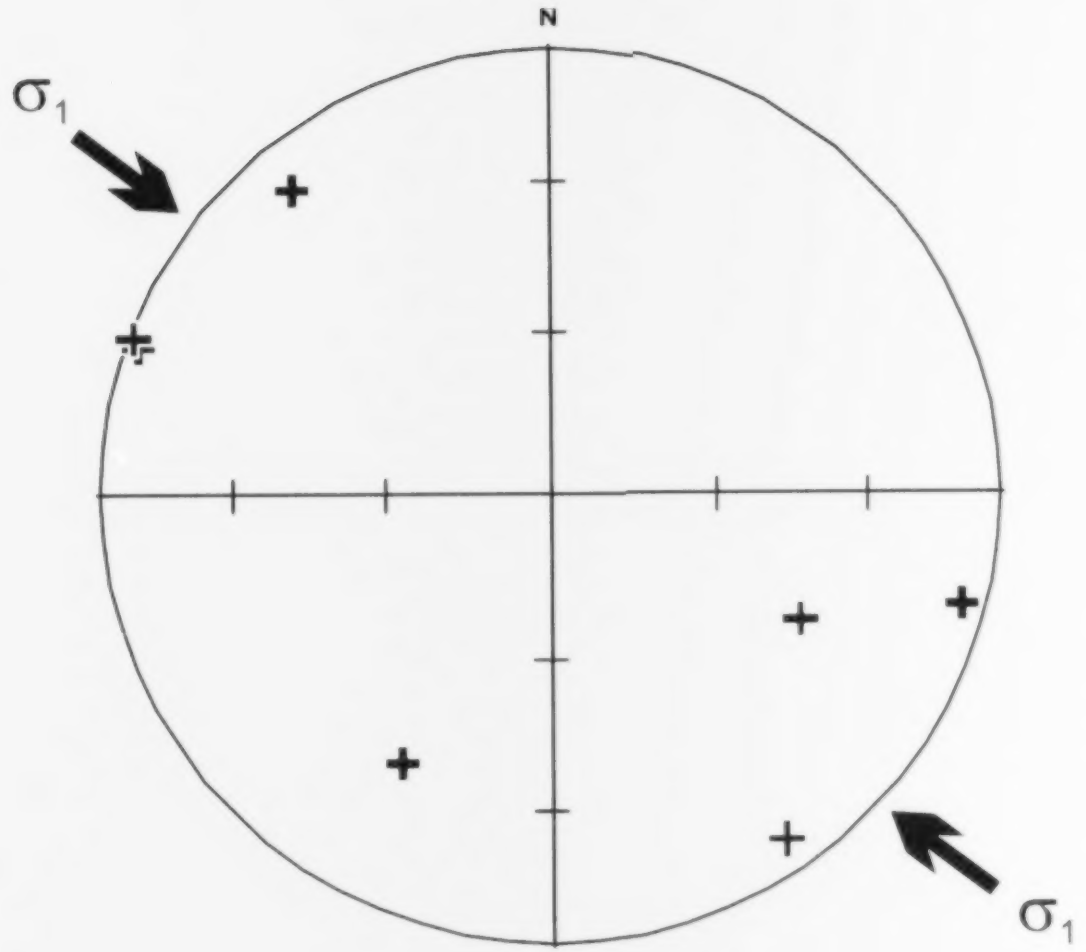

Figure 9. Maximum compression direction determined on 7 outcrops by inversion of striation orientations on fault planes (lower hemisphere equal-area projections). The maximum compression direction (σ_1) strikes northwest-southeast and is almost horizontal.

FORWARD MODELLING

The compilation of the field studies and the drill core observations led us to identify 2 important features. First, outliers of the Sudbury Igneous Complex were mapped close to the footwall contact, inside the footwall units (*see* Figure 3, back pocket). The precise shapes of the outliers is difficult to determine due to lack of sufficient outcrop, but they are clearly not contiguous with the main outcrop of the Sudbury Igneous Complex. Second, structural imbrication of the Sudbury Igneous Complex and the footwall were

documented in the drill cores, suggesting that the outliers of the Sudbury Igneous Complex are likely fault-bounded. Notably, the imbrications of the footwall rocks and the Sudbury Igneous Complex occur on shallowly dipping faults which are not likely related to the more steeply dipping South Range shear zone. An example of structural imbrication identified in two drill cores is shown in Figure 10. The imbrication can be traced between drill cores that are a few hundred metres apart (*see* Figure 10).

In order to model the structural repetition of rock units observed both in map and in drill holes, we prepared several models based on different working hypotheses that were consistent with the available data.

Model 0

In Model 0 (Figure 11: Chart A, back pocket), the deformation is entirely accommodated by 3 parallel reverse faults which represent the thrusting that occurred on the South Range shear zone. The resulting model shows that thrusting on the South Range shear zone could lead to layer repetitions in vertical sections, as observed in drill cores; however, the single-stage deformation in the model is unable to create the footwall/sublayer/norite - sublayer/norite repetitions documented on our revised map of the southwestern Sudbury Structure.

In the three following models we incorporate early, pre-thrusting normal faults that are subsequently deformed by thrusting on the South Range shear zone. We did not identify any pre-thrusting normal faults in the study area; however, their incorporation into the models is justified by the results of previous studies and by the documentation of several structures elsewhere in the Sudbury Basin. For example, Scott and Spray (2000), Scott and Benn (2001, 2002) and Snyder et al. (2002) all argued for a normal faulting stage very early in the deformation history of the Sudbury Igneous Complex. In models 1, 2 and 3 we introduce early normal faulting events, in each case with a different displacement on the normal faults. Justification for the chosen orientations and displacements on normal faults are provided for each model.

Model 1

Snyder et al. (2002) concluded that an early stage of normal faulting accommodated the collapse of blocks of the partly solidified Sudbury Igneous Complex in the northeastern part of the Sudbury basin. The normal fault they identified, using seismic-reflection data, dips shallowly (15°) toward the centre of the igneous complex. We introduced two shallow, northeast-dipping, (i.e., for the study area, dipping toward the interior of the Sudbury Igneous Complex) normal faults in Model 1. The total horizontal displacement on the modelled faults is roughly 2 km, which would correspond to the collapse into the Sudbury Igneous Complex of an already solidified basal part of the complex, prior to the South Range shear zone shortening event. As in Model 0, 3 reverse faults accommodating a total horizontal shortening of 4.2 km are modelled to illustrate the South Range shear zone deformation. The resulting model shows a duplication of the stratigraphy into blocks bounded by thrust faults of the SRSZ (Figure 12: Chart A, back pocket). The resulting outliers of the Sudbury Igneous Complex have rectangular shapes in plan view. Model 1 manages to reproduce structural repetition as observed on our geological map (*see* Figure 3) and in drill core.

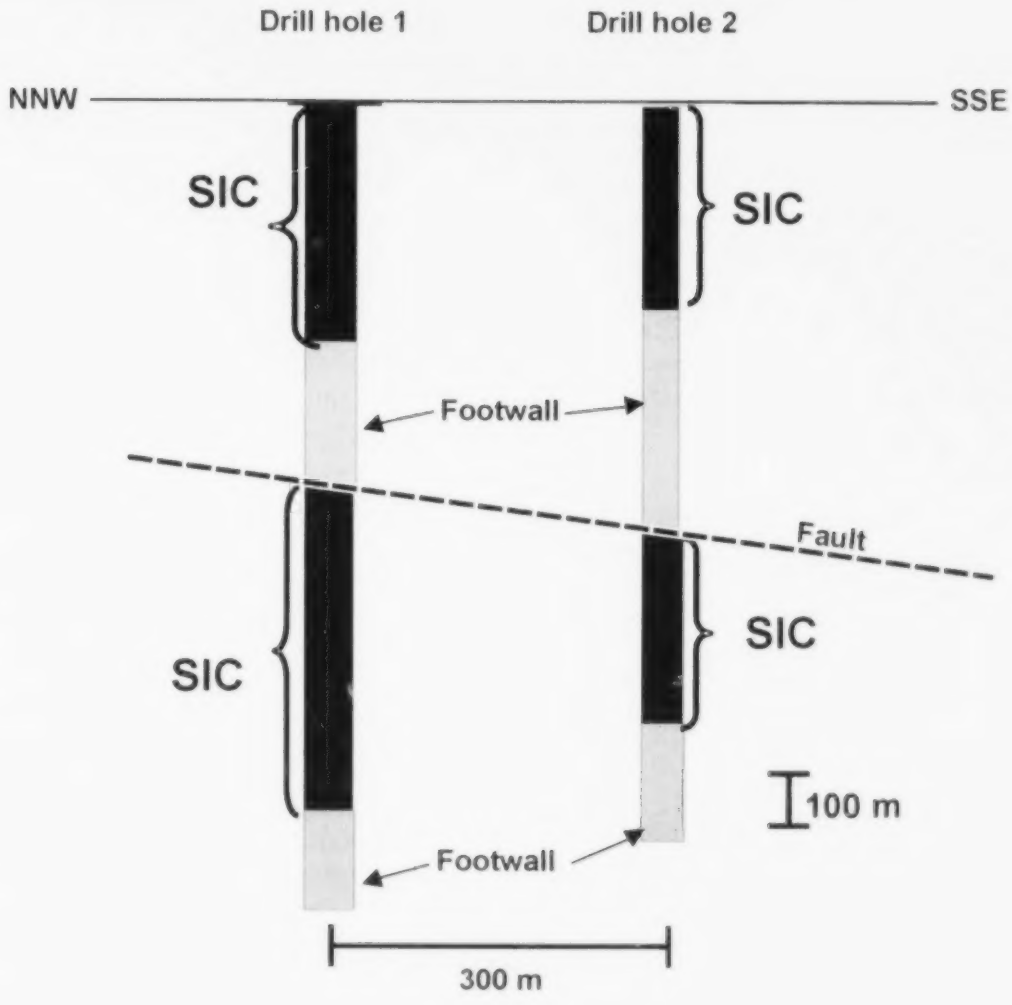

Figure 10. Example of structural imbrication identified in two drill holes, spaced 300 m apart.

Model 2

The Murray fault is a long-lived structure. It is presumed to have originated as a normal fault (Card and Hutchinson 1972) that was later reactivated as a thrust fault during the Penokean Orogeny (Cooke 1946) and as a strike-slip fault during the Grenville Orogeny (Card 1968; Zolnai, Price and Helmstaedt 1984). At the time of the Sudbury event, a broad zone of crustal extension resulted in normal movement on the Murray fault (Roscoe and Card 1992). The Creighton fault parallels the Murray fault and its western extremity lies in the study area. The last displacement on the Creighton fault was dextral strike-slip. The hypothesis of a normal fault, parallel to the Murray-Creighton fault system, and affecting the cooling

Sudbury Igneous Complex, is tested in Model 2. A total horizontal displacement of 600 m is accommodated by a modelled normal fault striking 100° and dipping 60° toward the south; with 3 later reverse faults accommodating a total horizontal displacement of 7 km to illustrate the shortening produced by the South Range shear zone. It leads to the individualization of triangular-shaped blocks of the base of the igneous complex within the footwall. These triangular outliers are bounded by thrust faults of the SRSZ (Figure 13: Chart A, back pocket). As detailed mapping in the areas of structural repetition was not possible due to lack of outcrop, the exact shape of the mapped outliers of Sudbury Igneous Complex rocks are not well constrained, so this model may reproduce structural repetition as observed on the geological map and in drill core.

Model 3

The northern part of the Sudbury Igneous Complex underwent less thrust-related deformation than did the study area. Accordingly, the angular shape of the northeastern corner of the Sudbury Igneous Complex is thought to be an original feature (Cowan, Riller and Schwerdtner 1999).

Our interpretation of the angular corners of the Sudbury Igneous Complex is based on an analogy with Meteor Crater, Arizona. Its rimcrest has an angular shape (Figure 14). This uncommon feature for a crater has been interpreted as the result of an impact in a terrain already fractured by orthogonal sets of joints (*see* Figure 14, data from Shoemaker 1963; in Melosh 1989). The northeastern corner of the Sudbury Igneous Complex displays contacts with the footwall trending 070° and 160°. We propose the following hypothesis: a fracture (or fault) set, composed of steeply dipping fractures orientated 070° and 160°, may have existed prior to the impact and may have influenced the original shape of the Sudbury Igneous Complex.

Model 3 tests the hypothesis that pre-impact fractures or faults, oriented 070°, were reactivated as normal faults prior to the South Range shear zone thrusting. The total modelled horizontal displacement is 500 m. It is accommodated by 2 normal faults striking 070° and dipping 60° southeast. Three later reverse faults accommodating a total horizontal shortening of 6.4 km illustrate the South Range shear zone deformation. The resulting model gives triangular outliers of the base of the Sudbury Igneous Complex within the footwall. The outliers are bounded by thrust faults of the South Range shear zone (Figure 15: Chart A, back pocket). This model manages to reproduce structural repetitions as observed on geological maps and in drill core.

GEOPHYSICAL MODELLING

In the previous section, we demonstrated three possible structural models that successfully explain the new map and drill-core data. Common to all three successful models is an early normal faulting event that predates thrusting on the South Range shear zone.

In order to sort out which of models 1, 2 or 3 could best explain the three-dimensional geology of the study area, gravity and magnetic maps are calculated from the three-dimensional block diagrams (*see* Figures 12, 13 and 15). Unfortunately, the present geophysical data sets of the study area (Figure 16: Chart A, back pocket) cannot resolve the complicated geology. Thus, the modelled geophysical maps will be most useful when compared with as yet unavailable, higher-resolution geophysical maps.

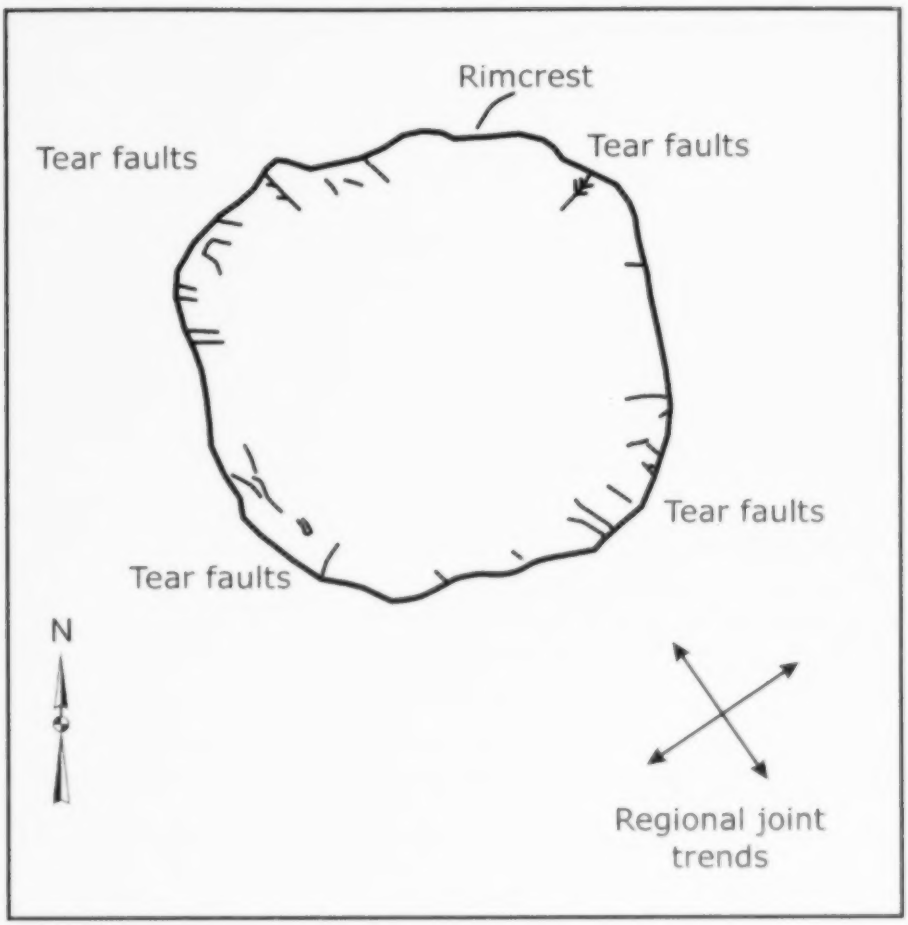

Figure 14. Meteor Crater's rimcrest, Arizona (data from Shoemaker 1963, in Melosh 1989).

Modelled Gravity Maps

To produce model gravity maps, a unique density value was attributed to the footwall rocks (2.7 g/cm^{-3}). This value is an average of Huronian and Archean densities determined from data in McGrath and Broome (1992) for the Sudbury area. Granophyre density is about 2.66 g/cm^{-3} in the Fairbank Lake area (Gupta, Grant and Card 1984). A single density value is also set for the sublayer and norite layers (2.81 g/cm^{-3}).

Thrust faults are recognized on the three modeled gravity maps derived from the three geological models (Figures 17, 18 and 19: Chart A, back pocket). Normal faults can also be pointed out in Models 2 and 3 that lead to triangular shapes of the outliers of the Sudbury Igneous Complex within the footwall. On the other hand, Model 1 shows a thickening of the base of the Sudbury Igneous Complex (*see* Figure 17). Normal faults are not directly recognizable in the gravity map generated from Model 1, but they are responsible for the thickening. Comparison of the modelled gravity maps with the available gravity map of the area (*see* Figure 16) is not easy, because of the aforementioned low resolution of the published map.

Modelled Magnetic Maps

A unique magnetic susceptibility value is attributed to the footwall (100.10^{-6} USI). This value is an average of Huronian and Archean magnetic susceptibility values determined from data in Hearst, Morris and Thomas (1992) for the Sudbury area. Granophyre magnetic susceptibility is about 25.10^{-6} USI in the Fairbank Lake area. A single magnetic susceptibility value is set for the sublayer and norite layers (60.10^{-6} USI).

Thrust faults are recognized on the three modelled magnetic maps derived from the three blocks (Figures 20, 21 and 22: Chart A, back pocket). Model 1 shows a thickening of the base of the Sudbury Igneous Complex by a repetition of the footwall/SIC contact. A normal fault is parallel to the contact, so, the difference in magnetic susceptibility values observed on the calculated map might be linked with a normal footwall/SIC contact, regardless of whether there is a fault. In this case, the calculated magnetic map does not allow identification of normal faults associated with the collapse into the Sudbury Igneous Complex.

When the Sudbury Igneous Complex outliers are well-defined in the footwall, they are easily recognized on the calculated magnetic maps. Normal faults can then be pointed out in Models 2 and 3. Comparison of the modelled magnetic maps with the available magnetic map of the area is not easy, again because of the low resolution of the publicly available map. In future, however, higher resolution gravity and magnetic data sets, may well allow for discrimination of normal and reverse faults in the study area, and the further refinement of the three-dimensional models.

Summary

Data and observations gathered during this project, along with the results of three-dimensional modelling, allow us to propose the following post-Sudbury event structural evolution for western Sudbury Structure.

The Sudbury Igneous Complex, and its footwall, were probably affected by an early generation of normal faults. The early normal faulting would have occurred as the Sudbury Igneous Complex cooled. We have not documented any early normal faults during mapping; however, structural analysis and three-dimensional modelling require an early stage of normal faulting to explain the present structural imbrication of different units. Early stages of normal faulting, coincident with cooling of the Sudbury Igneous Complex, have also been proposed by previous workers for other parts of the Sudbury Structure. Our modelling does not allow us to tightly constrain the orientations and displacements on early normal faults; however, refinements to the models could be carried out in the future if high-resolution geophysical data sets become available.

Northwest-vergent oblique thrusting on the South Range shear zone post-dated normal faulting and began during cooling of the Sudbury Igneous Complex. Thrusting on the South Range shear zone continued long enough to significantly shorten the South Range of the Sudbury Structure and to generate mylonites during strong shearing and dynamic recrystallization. South Range shear zone deformation imbricated the Sudbury Igneous Complex, locally thrusting the norite unit over the granophyre unit, to the north of Fairbank Lake. The South Range shear zone also deformed footwall rocks and contributed to the imbrication of the footwall with the Sudbury Igneous Complex, as suggested by the results of three-dimensional modelling. We attribute the South Range shear zone deformation to early stages of the Penokean Orogeny. That interpretation implies that the early stages of the Penokean Orogeny would have been concomitant with cooling of the South Range shear zone. Potential normal-sense displacements

within the South Range shear zone are also suggested but further detailed studies would be required to confirm that hypothesis.

A second, though apparently minor ductile deformation event resulted in crenulation of the South Range shear zone fabric and, locally, the formation of a crenulation cleavage striking 110°. This deformation event is possibly linked with reactivation of faults associated with the Murray fault system, perhaps late during the northwest-vergent thrusting event.

Brittle faulting post-dates all ductile deformation in the study area. Paleostress analysis suggests that brittle faulting may record northwest-southeast shortening of the Sudbury Basin associated with a late phase of the Penokean Orogeny. At least three groups (based on orientations) of brittle faults are recognized throughout the study area. Within the South Range shear zone, many brittle faults appear to have reactivated the pre-existing, strongly developed, mylonitic foliation.

Implications for Mineral Exploration

The study area may be the most structurally complex part of the Sudbury Structure. Successful mineral exploration programs should therefore benefit from the extensive structural analyses and modelling presented in this study. The main types of ore bodies exploited within the Sudbury basin are well known and documented (Morrison, Jago and White 1992) and include:

1. contact deposits associated with the sublayer and situated within apparent depressions at the base of the Sudbury Igneous Complex;

2. offset dike deposits that are exploited within quartz-dioritic dikes that are interpreted to be impact melts injected into fractures in the footwall rocks;

3. footwall ore bodies that are interpreted as differentiates of the contact ore bodies.

Other ores may have been generated by post-impact hydrothermal events that remobilized and concentrated metals within the Sudbury Breccia (Watkinson 1994).

Mapping during this study has identified the extent of the South Range shear zone, showed that early South Range shear zone thrusting was probably contemporaneous with cooling of the Sudbury Igneous Complex, and identified outliers of the Sudbury Igneous Complex within the footwall near the footwall/SIC contact. Drill core observations demonstrate structural repetition in the subsurface. The increased understanding of the structural complexity of the study area provides at least 2 important insights for mineral exploration strategies.

First, the structural imbrication of the Sudbury Igneous Complex with the footwall rocks shows that potentially mineralized rocks of the basal parts of the Sudbury Igneous Complex should be sought within the outcrops of the main Sudbury Igneous Complex, and also in areas where outliers of footwall rock occur. We suggest that further detailed mapping and structural analyses should be combined with high-resolution geophysics and three-dimensional modelling, in order to target potentially mineralized rock bodies in the subsurface.

Second, if an early stage of normal faulting, and also early South Range shear zone thrusting, were contemporaneous with cooling of the Sudbury Igneous Complex (as suggested by our study), then impact melts and impact-related fluids may have been influenced by the faults and/or shear zones. Such melts and fluids were certainly important in the genesis of Sudbury ore deposits. Hence models for the origins

of mineral deposits in the study area, and perhaps elsewhere in the South Range of the Sudbury Basin, should consider that faulting may have influenced the genesis and the location of some potential deposits, both in the footwall and in the Sudbury Igneous Complex.

Three simple models are presented that could explain the three-dimensional geology and structure of the study area. The extent of present knowledge of the geology and structure of the area does not allow us to establish which of the structural histories depicted in the three successful models is closest to the actual history of the area. However, the geophysical maps that were generated from the models suggest that, by using higher-resolution geophysical data than are presently available in the public domain, exploration programs may be able to test and further refine the models.

We offer 2 suggestions that should be of use for future mineral exploration programs in the Sudbury Structure.

1. Future detailed mapping projects should include relogging of available diamond-drill cores from any properties of interest. The relogging of existing drill cores, and any new exploration diamond-drill cores, should include petrographic study of representative rock types. Petrographic study is especially useful to identify original rock types that may be difficult to recognize in the cores using only a hand lens, due to a locally pervasive greenschist-grade metamorphic overprint present in the South Range. Logging of drill cores should also include systematic structural observations, and should seek to identify faults and/or shear zones that may have accommodated structural repetition of units, and thickening (by thrusting) or thinning (by normal faulting) of units. In this study, the combination of mapping and relogging of diamond-drill cores proved to be very successful in establishing the three-dimensional geology. It also provided the essential information for the forward modelling of the structural evolution of the region.

2. Once three-dimensional models are established for an area, high-resolution geophysical data and rock properties measurements are needed to test and refine the models. Geophysical anomalies that cannot be explained by well-constrained geological models may indicate potential exploration targets.

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Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.